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THE EXCITATION OF THE SPECTRA OF NITROGEN BY ELECTRON IMPACTS

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ABSTRACT

The excitation of the spectra of nitrogen was investigated by two methods: (1) in low-voltage arcs in a mixture of nitrogen and mercury vapor below the ionizing potential, and (2) in a three-element tube at low pressures.

The first, second, and fourth positive bands appeared below the ionizing potential, and are assigned to the neutral molecule. Three new low-potential systems are reported in the ultra-violet. These, also, are assigned to the neutral molecule. The third positive bands did not appear, and are probably due to a nitrogen oxide. The cyanogen bands were likewise absent.

The negative bands appear above the ionizing potential and increase in intensity with the degree of ionization, being emitted by the ionized molecule. New bands in the ultra-violet, degraded toward the red, appear simultaneously and, in addition to exhibiting a similar behavior, have the same Deslandres progression, indicating a physical relationship.

The line spectrum appeared above about 70 volts in ordinary arcs and as low as 35 volts in intense arcs, in agreement with the change in the rate of clean-up of nitrogen in the discharge.

Nitrogen has, in addition to a rich line spectrum, quite a number of band spectra, or band systems. Some of these systems have commanded considerable attention since the original work on the classification of band spectra, and, without a doubt, the same systems are destined to play a very important rôle in the future development of the theory of band spectra in general.

The principal band systems of nitrogen were originally classified

by Deslandres[1] as the first, second, and third positive groups and the negative group. This nomenclature was adopted in order to distinguish between those groups which, in the ordinary Geissler-tube discharge, appear with maximum intensity in the positive column and the group which appears with maximum intensity in the negative glow. These bands, in particular the second positive group and the negative group, served Deslandres quite admirably in arriving at the formulation of the laws which bear his name and in establishing the formulae which have played such an important part in the early theory of band spectra.

In addition, however, to these so-called Deslandres groups nitrogen has a number of other band systems. Some of these systems behave quite differently under given conditions of excitation. In fact, it is possible to excite some of these families without having the slightest trace of others.

Baly, as recently as 1912, in describing the primary and secondary spectra of hydrogen and other cases of so-called plurality of spectra writes:

> These cases of plurality of spectra serve to show what an interesting field of work lies here; no explanation has yet been found of the curious facts described, and there is room for a great development of our knowledge in this direction.[2]

The years that have intervened have witnessed such a development, and our knowledge in this direction is increasing at a very rapid pace. It is now generally believed that the various separated divisions of the spectrum of a substance such as nitrogen may be attributed to the presence in the emitting source of molecules in various states of association, dissociation, and ionization, each type of molecule or atom giving rise to its own characteristic radiation.

The purpose of the present investigation was to excite the spectrum of nitrogen under such conditions as would permit one to determine, at least approximately, the minimum amount of energy required for the excitation of each of the several divisions of the nitrogen spectrum, and to study the behavior of these various groups of rays under different conditions of excitation. In this way it is possible, not only to assign each group to its proper emission

[1] *Comptes Rendus*, **100**, 1259, 1885, *et seq.* [2] Baly, *Spectroscopy*, p. 525.

center and to establish certain physical relationships between the groups, but, also, to gain some information relative to the several stages of excitation of a given emitter, the neutral molecule, for example, before and after the emission of the several divisions of the spectrum which are assigned to it.

With this in view, a spectrographic study was made of the radiations emitted by nitrogen gas when excited by electrons of known velocities. In the course of the investigation three somewhat different sources of radiation were used. During the early stages, a low-voltage arc maintained in nitrogen alone in a simple two-element, hot cathode tube served as the source of excitation. In order to use the arc as the source of radiation for accelerating voltages below the ionizing potential of nitrogen—it being impossible to maintain the arc in a diatomic gas much below the ionizing potential—mercury was introduced into the experimental tube and the relative pressures of mercury vapor and nitrogen gas regulated by temperature control. As a second source of radiation, the simple two-element tube was replaced by a three-element tube in which the grid and plate were connected to form the anode. The latter tube was provided with a quartz window through which the force-free region between the grid and filament could be projected, by means of a quartz lens, upon the slit of the spectrograph. The grid in this tube was distant about 0.7 cm from the filament, and the nitrogen pressures used extended over the range (0.6–0.003) mm.

Objection might be offered to these sources of radiation, as used, on the ground that the potential applied between the filament and the plate is not necessarily a measure of the velocity of the impacting electrons inasmuch as the electrons would undergo frequent collisions with gas molecules during transit from filament to plate, and consequently, might, in the two-element tube, reach the plate or, in the three-element tube, enter the force-free region between grid and plate with velocities varying anywhere from zero as a minimum to the applied accelerating potential as a maximum. To obviate this difficulty, a third experimental tube was used. The general form of this tube is shown in Figure 1. It consisted of a pyrex-glass tube about 30 cm in length and 5 cm in diameter, provided at either end with a hollow ground-glass stopper. One end carried the plate sup-

port, the other the filament leads and grid support. The grid in this case was a platinum gauze covering a small rectangular hole about 2×1 cm in the end of a cylindrical nickel shield inclosing the filament. The distance between filament and grid could be varied. This was made so small that, for the low pressures used, collision of electrons with gas molecules in this region was infrequent and it could safely be assumed that the electrons from the hot filament

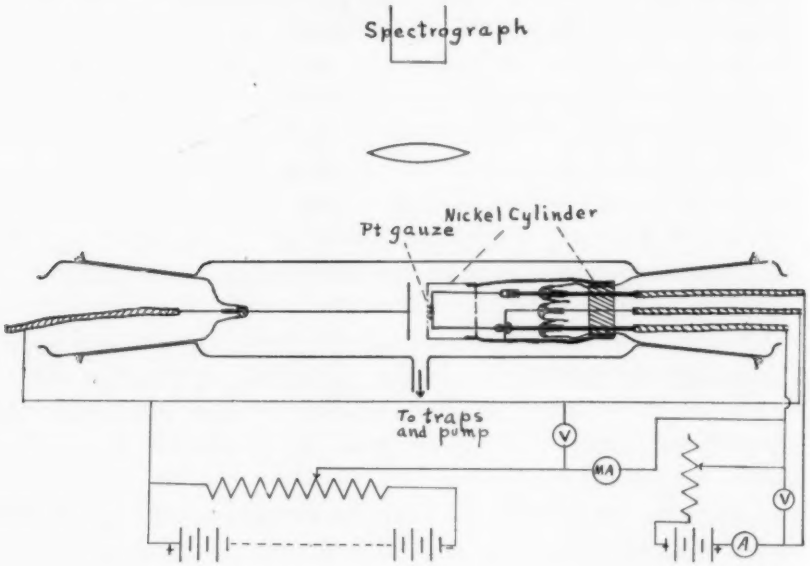


FIG. 1

entered the force-free region between grid and plate with a velocity equivalent of the accelerating potential applied between filament and grid.

Observations obtained using a source of radiation of this latter type agree very favorably with those obtained using experimental tubes of the two former types. This is to be expected if the theory of the low-voltage arc as developed by Duffendack[1] be a correct explanation of the phenomena. For if the redistribution of the electric intensity in the tube which accompanies the striking of the arc is such that practically the entire potential difference applied between

[1] *Physical Review*, **20**, 668, 1922.

the electrodes is distributed over a space interval in the immediate vicinity of the cathode of the order of magnitude of the mean free path of an electron in nitrogen for the pressures used, then it is obvious that the electrons on first impact will have a velocity equivalent only slightly less than the applied potential difference. The successive excitation of the first two lines of the Balmer series at their radiating potential which has recently been reported by Duffendack[1] confirms this view.

The nitrogen used was prepared and purified by the method described by Waran.[2] Pure bromine water was dropped into pure ammonia solution. The nitrogen produced by the interaction was bubbled through a concentrated solution of *KOH* which served to remove any ammonia and bromine which might be mixed with the nitrogen. It was next passed through hot copper turnings to remove any traces of oxygen which may have come from dissolved air in the liquids, and then, prior to being admitted into the experimental tube, was stored in a compartment containing phosphorus pentoxide.

To make certain that some of the new bands observed were not due to impurities in the gas, several samples of nitrogen were used which had been prepared by slowly heating a mixture of sodium nitrite and ammonium sulphate. No differences, however, were observed on the spectrograms obtained from the nitrogen prepared by the two methods. Since these new band systems did not appear when the nitrogen was replaced by other gases, hydrogen and oxygen, it is safe to assume that they are due to nitrogen.

In preparing for each "run" the experimental tube was baked out for a period of six hours in an electric oven maintained at a temperature of 350° C. The pumps were operated continuously during this baking-out process. At frequent intervals during the last stages of baking, the filament was heated to a white heat, and nitrogen admitted and pumped out several times to get rid of any other occluded gases which might be present in the apparatus. The nitrogen used passed through a liquid-air trap just before entering the experimental tube. Pressures were measured with a McLeod gauge.

The low-voltage arc, as used in the greater part of this investi-

[1] *Op. cit.*, **23**, 107, 1924; *Astrophysical Journal*, **60**, 122, 1924.

[2] *Philosophical Magazine*, **42**, 246, 1921.

gation, affords a very satisfactory source of excitation in that the energy of the impacting electrons can be readily controlled and measured, and, the arc being a region of very intense excitation, satisfactory spectrograms may be obtained with relatively short exposures.

Results.—Several series of spectrograms were obtained under different experimental conditions covering the spectral region λλ 7000–2000 A. A careful examination of these spectrograms leads to some very definite information relative to the amount of energy required to excite each of the several divisions of the nitrogen spec-

TABLE I

Band System	End of Spectrum toward Which Bands Are Shaded	Excitation Potentials in Volts
First positive (Deslandres)	More refrangible	9.5± .5
Second positive (Deslandres)	More refrangible	12.0± .5
Fourth positive (Strutt)	More refrangible	15.0± .5
Fifth positive	More refrangible	10.0± .5
Sixth positive	More refrangible	15.5± .5
Seventh positive	Less refrangible	12.0±1.0
First negative (Deslandres)	More refrangible	18.0± .5
Second negative	Less refrangible	18.5± .5
3464	More refrangible	15.0± .5
3021.2	Less refrangible	13.0± .5

trum within the region studied. This information, together with the knowledge acquired from a study of the behavior of each group of rays under different physical conditions, should make it quite possible to predict the probable origin of each of these several groups.

The band spectrum of nitrogen within this particular spectral range apparently comprises, in addition to the first, second, and fourth positive bands and the negative band systems which have been previously ascribed to it, at least four other groups or systems which are designated in this paper, for reasons that will appear later, as the fifth, sixth, and seventh positive systems, and the second negative band system. Also, there are two individual bands, one with head at 3464 A, and the other with head at 3021 A. These several band systems with their direction of shading and corresponding excitation potentials are given in Table I.

First positive group.—This system, part of which appears on

PLATE I

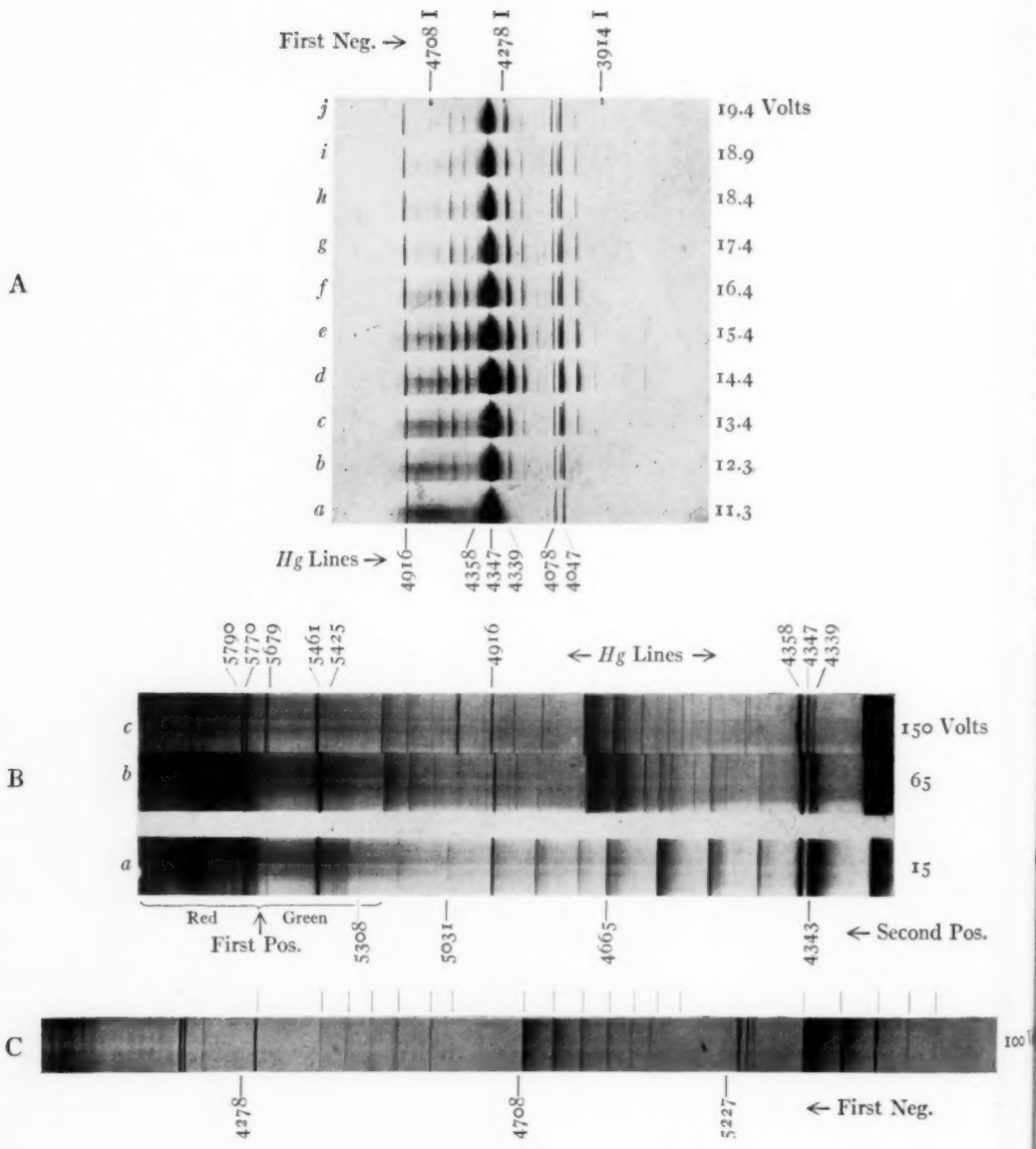

A
First Neg. →
4708 I
4278 I
3914 I
j
i
h
g
f
e
d
c
b
a
19.4 Volts
18.9
18.4
17.4
16.4
15.4
14.4
13.4
12.3
11.3
Hg Lines →
4916
4358
4347
4339
4078
4047
B
5790
5770
5679
5461
5425
4916
← Hg Lines →
4358
4347
4339
c
b
a
150 Volts
65
15
Red
Green
First Pos.
5308
5031
4665
4343
← Second Pos.
C
100
4278
4708
5227
← First Neg.

Plate I A, B, begins at about λ 9100 and extends over the greater portion of the visible spectrum. It comprises three more or less separate groups of bands—red, yellow, and green, respectively. While this system was not fully developed until the impacting electrons had attained a velocity equivalent of 12.5 volts, the principal components appeared at 10 volts. A twelve-hour exposure at 9 volts bore no trace of these bands, but they appeared, although quite faintly, on a three-hour exposure at 10 volts. The behavior of this system under different physical conditions has been variously reported on by Rayleigh, Lewis, and others. Fowler and Strutt,[1] while investigating the spectrum of the nitrogen afterglow, were led to the conclusion that the remarkable red, yellow, and green bands in the afterglow spectrum, originally observed by Lewis,[2] were a selection of the first positive nitrogen band system. In a more recent work Rayleigh[3] has shown that the particular selection can be greatly modified by admixture of the inert gases, the effect of adding an inert gas being to shift the maximum of intensity in each group toward the red. Addition of helium in particular made the red group, as a whole, more intense at the expense of the others. In the present investigation the relative intensities of the three divisions did not change appreciably as the conditions of excitation were altered. Change of pressure, current, or voltage had no noticeable effect on the appearance other than to alter the intensity of the group as a whole. This, for a given current, appeared to reach a maximum at about 15 volts.

Second positive group.—This begins in the violet and extends to about λ 2800. The bands in this system, as seen from Plate I (A, B*a*) and Plate II (A, B), have their heads toward the red end of the spectrum. The band heads are gathered in groups of five; except toward the head of the system where there is a group of two bands, then one of three, one of four, and finally the sequence of fives. It is of interest to note in passing that, on all of the spectrograms obtained, the last two members of the group with head at λ 3577 are greatly suppressed. The strongest members of this system appear faintly at

[1] *Proceedings of the Royal Society*, A, **85**, 377, 1911.

[2] *Astrophysical Journal*, **20**, 49, 1904; *Philosophical Magazine*, **25**, 826, 1913.

[3] *Proceedings of the Royal Society*, A, **102**, 453, 1923.

12 volts, and the entire system develops shortly after this, reaching a maximum between 14 and 15 volts, as may be seen by reference to Plate I A. This spectrogram was obtained using as source of radiation a low-voltage arc in a mixture of nitrogen and mercury vapor in a simple two-element tube. It shows, consequently, in addition to the second positive bands, all the prominent mercury lines in this region of the spectrum. Also, the exposures at the three higher voltages show the coming in of negative band heads to which reference will be made later.

Plate II A was obtained by photographing the radiation from a three-element tube containing nitrogen alone. This particular series of spectrograms is shown merely to call attention to the presence of the chief members of the several groups on the 13-volt exposure with no evidence of the weaker members of these groups. It should not be inferred from the appearance of these spectrograms that the intensity of the second positive bands increases with increasing accelerating voltage. The exposures at the two higher voltages were taken after the striking of the arc, and the marked increase in the intensity of the bands here is due not so much to the increase in the voltage as to the enormous increase in the electron stream accompanying the striking of the arc.

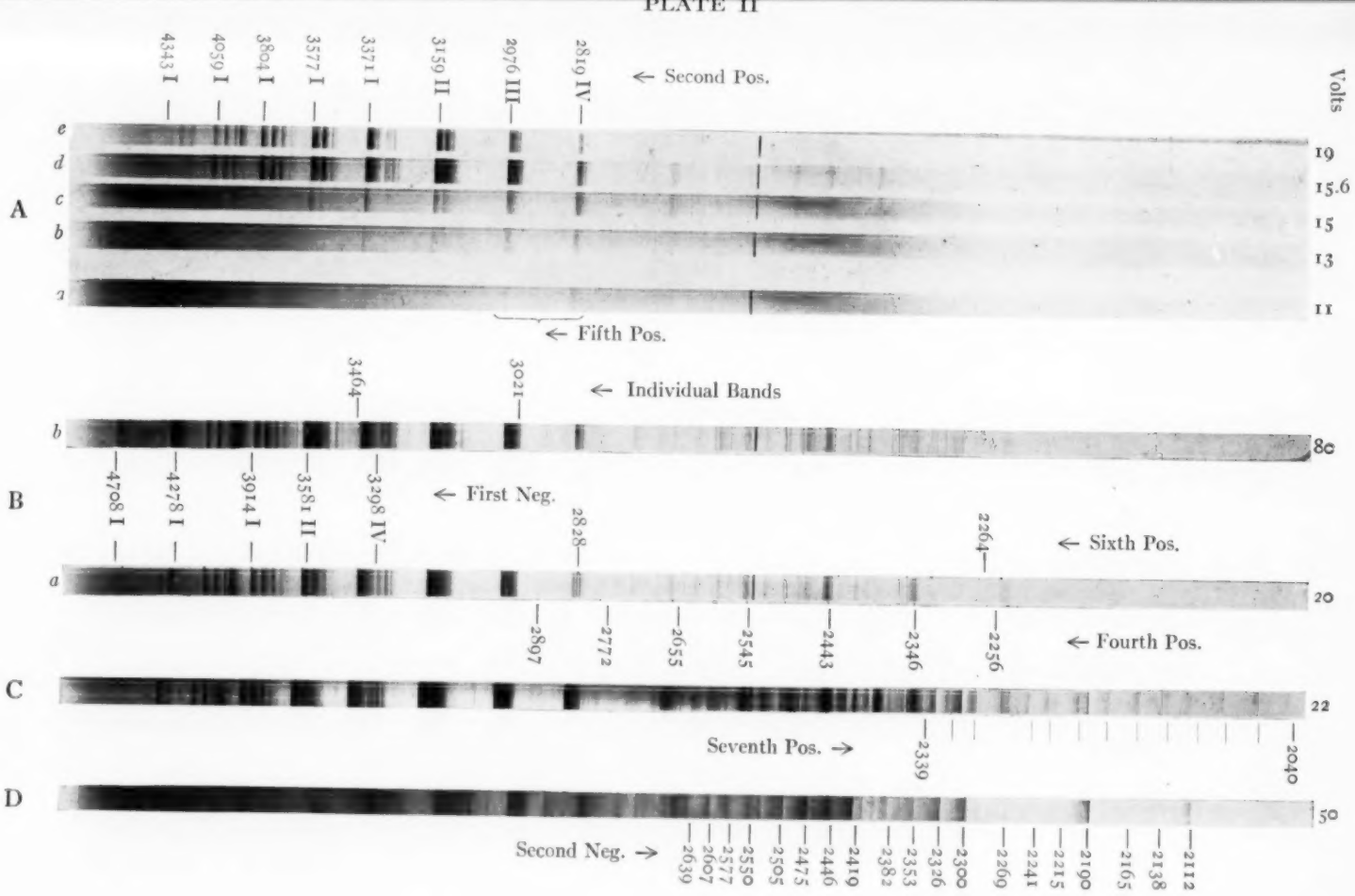
Fourth positive group.—This system, shown on Plate II B, was originally reported by Fowler and Strutt.[1] It consists of seven groups extending over the region λλ 2900–2250. Each group comprises five principal heads of which the most refrangible is the strongest in each case. This system appears first faintly at 15 volts. The intensity increases slightly at first with the accelerating potential, reaches a maximum for about 20 volts, and then decreases with further increase in voltage.

Fifth positive bands.—This low-potential system appearing rather indistinctly on Plate II A, B, consists of two groups which bear a very striking resemblance to Strutt's fourth positive groups. Each group comprises four band heads of which the most refrangible is by far the most intense. The intensity of the other heads decreases with the degree of refrangibility, the two least refrangible heads being very faint. The behavior of these groups with increased volt-

[1] *Proceedings of the Royal Society*, A, **85**, 377, 1911.

PLATE II

PLATE II


4343 I
4959 I
3804 I
3577 I
3371 I
3159 II
2976 III
2819 IV
← Second Pos.
Volts
A
e
d
c
b
a
19
15.6
15
13
11
← Fifth Pos.
3464
3021
← Individual Bands
b
80
B
4708 I
4278 I
3914 I
3581 II
3298 IV
← First Neg.
2828
2264
← Sixth Pos.
a
20
2897
2772
2655
2545
2443
2346
2256
← Fourth Pos.
C
22
Seventh Pos. →
2339
2040
D
50
Second Neg. →
2639
2607
2577
2550
2505
2475
2446
2419
2382
2353
2326
2300
2269
2241
2215
2190
2165
2138
2112

age is not obvious from the spectrograms since they fall so close to the first two groups of the second positive system that they are soon shaded out by the latter. They apparently have the same critical potential as do the members of the first positive system. Appearing first faintly at 10 volts, they attain maximum intensity at about 20 volts. The series notation, wave-length, intensity, and corresponding wave-number for each of the band heads belonging to this system are given in Table II. The intensity is rated on a basis of 10 for the head of maximum intensity in this system.

It is quite apparent that this band system is closely related to the second and fourth positive systems, as may be seen by a con-

TABLE II

FIFTH POSITIVE BANDS

Series Notation	Wave-Length	Intensity	Wave-Number	Difference
I	2973.2	1	35,324	
II	2971.6	1	35,344	
III	2969.3	2	35,366	
IV	2968.2	5	35,394	
I	2830.9	2	33,633	1704
II	2829.3	2	33,652	
III	2827.8	6	33,677	
IV	2825.3	10	33,690	

sideration of their series relationships. In the first, third, and fifth columns of Table III are recorded the wave-numbers of the last two terms of the fourth series of the second, fourth, and fifth positive bands, respectively. The wave-number intervals, 82 and 83, between the corresponding terms in the first and third column are equal within the limits of error. The same is true of the differences 8916 and 8919 between corresponding terms of the fourth and fifth positive bands. Also the wave-number interval, 1704, for the strongest heads of this system, recorded in the last column of Table II, is equal, within the limits of error, to the corresponding intervals 1704 and 1705 between the last two terms of the fourth series of the second and fourth positive band systems, respectively. Numerically, at least, then, the fifth positive bands are related to the second and fourth positive bands.

Sixth positive bands.—This system, shown on Plate II B, extends over the region λλ 2828–2111. The general character of this group is quite different from that of the groups described above, as may be gained from the plates. Series relationships for this and the next succeeding system have not been established as yet. Appearing

TABLE III

Second Positive Series IV	Difference	Fifth Positive Series IV	Difference	Fourth Positive Series IV
33,772	82	33,690	8916	42,606
35,477	83	35,394	8919	44,313

first at 15.5 volts, this system increases in intensity with increased voltage, attaining a maximum of intensity at approximately 20 volts. Further increase in accelerating potential has only very slight effect on the appearance of the groups. The wave-lengths for the bands of this system, and their approximate intensities on a scale of 10 for the strongest, are given in Table IV.

TABLE IV

SIXTH POSITIVE BANDS

Wave-Length	Intensity	Wave-Length	Intensity
2828.1	7	2431.6	2
2743.3	2	2418.0	1
2722.5	8	2412.0	8
2696.0	1	2355.4	8
2682.0	3	2322.7	2
2647.0	1	2303.7	2
2636.5	3	2274.9	1
2625.0	8	2264.1	8
2596.2	1	2245.0	2
2587.0	9	2236.3	2
2556.4	2	2222.2	1
2523.1	5	2182.0	7
2497.5	10	2166.0	6
2470.5	9	2111.0	4

Seventh positive bands.—The strongest members of this low-potential system are shown on Plate II C. The spacing of the partial band components here is very similar to that for the system of bands in the Schumann region photographed by Lyman.[1] While

[1] *Spectroscopy of Extreme Ultra-Violet*, p. 113, 1914.

in no case did this system appear with sufficient intensity to be detected at less than 12 volts it is quite possible that its critical potential is a volt or more below this value. For not only does the extreme faintness of this system make the exact determination of its critical potential difficult, but it is quite possible that the bands having the initial state zero, which should be the first bands of the system to be excited, as will be seen from the later discussion, lie beyond the range of the spectrograph. Like the other positive bands described here, this system is of maximum intensity for moderate potentials of the order of 20 volts. The wave-lengths and approximate intensities of the band heads of this system are given in Table V.

TABLE V

SEVENTH POSITIVE BANDS

Wave-Length	Intensity	Wave-Length	Intensity
2338.7	3	2173.7	8
2312.4	5	2151.1	10
2286.7	8	2128.7	5
2247.5	4	2107.1	2
2221.9	4	2088.0	3
2209.0	1	2064.0	4
2196.6	5	2040.0	4

First negative bands (*Deslandres*).—According to the original classification by Deslandres, this system consists of six groups of five bands each, extending from λ 5227 to λ 3296 with several members missing from some of the groups. It is of interest to note that the group with head at 5227 A for which only the first two components are reported in Kayser's *Handbuch der Spectroscopie* appears here with no less than seven bands, as may be seen from Plate I C. The low-voltage arc appears to provide a particularly favorable source for the excitation of the negative bands, for they become very intense at the higher voltages and show their fine structure. The bands of longest wave-length in the several groups appear first at 18 volts, as may be observed from Plate I A. It is significant that this is just above the ionizing potential of nitrogen (16.9 volts). With increasing accelerating potential the remaining members of the groups appear in order and the intensity of the entire system increases very markedly (Plate I B).

Second negative system.—The series classification, wave-lengths, approximate intensities, and corresponding wave-numbers for the bands of this system are given in Table VI.

It is suggested that this system be called the "second negative" in order to indicate the relationship, apparently very close, which exists between these bands and the negative bands of Deslandres just described. As may be seen from Plate II D, this system comprises five groups extending over the region λλ 2638–2112. Like

TABLE VI

SECOND NEGATIVE SYSTEM

Series	Wave-Length	Intensity	Wave-Number
IV	2638.6	4	37,899
III	2607.5	5	38,351
II	2577.5	5	38,797
I	2550.2	6	39,213
IV	2504.7	6	39,923
III	2474.6	8	40,410
II	2446.0	9	40,883
I	2419.2	10	41,336
IV	2382.5	2	41,972
III	2353.2	3	42,495
II	2325.3	5	43,006
I	2300.0	7	43,478
IV	2269.4	1	44,064
III	2241.0	1	44,622
II	2214.8	2	45,151
I	2190.2	6	45,658
IV	2165.0	1	46,189
III	2138.1	3	46,770
II	2112.5	5	47,335

the seventh positive bands, these bands are degraded toward the red end of the spectrum. Appearing first faintly at 18.5 volts, they undergo a very marked increase in intensity with increasing voltage. They have not only the same critical potential as the negative bands of Deslandres, but also identical series relationships, as may be seen from Tables VII and VIII.

The law governing the arrangement of the band heads in a band system, commonly known as the "second law of Deslandres," states that each series is so arranged that the intervals between the frequencies of successive heads form an arithmetical progression, and further, that all the series in a given band system are exactly similar

and may be obtained one from the other by adding or subtracting a constant. The wave-numbers of the first four series of the first negative system and the four series of this new system are given in Tables VII and VIII, respectively. The differences between the consecutive terms of the several series are given in the fifth column in each case.

TABLE VII

FIRST NEGATIVE BANDS

Series I	Series II	Series III	Series IV	Difference	Second Difference
25,545.....	27,917	.....	.....	2172	
23,370.....	25,746	28,060	.....	2134	38
21,236.....	23,604	25,923	28,180	2110	24
19,129.....	21,491	23,809	26,073	2072	38
.....	19,423	21,734	23,998	2039	33
.....	.....	19,699	21,954	2000	39
.....	.....	.....	19,954		
Average....	.....	.....	.....	.....	33

TABLE VIII

SECOND NEGATIVE BANDS

Series I	Series II	Series III	Series IV	Difference	Second Difference
45,658.....	47,335	.....	.....	2182	
43,478.....	45,151	46,770	.....	2144	38
41,336.....	43,006	44,623	46,189	2124	20
39,213.....	40,883	42,495	44,064	2087	37
.....	38,797	40,410	41,972	2054	33
.....	.....	38,351	39,923	2024	30
.....	.....	.....	37,899		
Average....	.....	.....	.....	.....	31

The average second difference, 33, of the first system is equal, within the limits of error, to the average second difference, 31, of the second system. These two systems then have the same Deslandres progression.

For the first negative system, the mean difference between series I and II is 2369, between series II and III it is 2315, and between series III and IV it is 2260. These differences also form an arithmetical series having an interval 54. This interval is identical with that of the series formed by the corresponding differences for the second nega-

tive bands. It is obvious, therefore, that the separate series of these two band systems are similarly constituted, and only differ from one another by a constant amount in each case. It will be seen from the discussion that follows that the fact that these two band systems have a common excitation potential and the same Deslandres progression makes it seem quite probable that they have the same initial state.

The individual bands, Plate II B*b*, with heads at λ 3464 and λ 3021.2, respectively, do not appear to be related to any of the band systems already described. The former, with its edge toward the red, appears first at about 15 volts and becomes very intense at the higher voltages, its fine structure extending throughout the second positive group with heat at λ 3371. The λ 3021.2 band is degraded toward the red, and has a slightly lower critical potential. It appears first at about 13 volts, but does not undergo any very marked change with increasing voltage.

Discussion.—As indicated above, these several band systems are affected quite differently by physical conditions. The majority of the systems described, as has been seen, appear at voltages considerably below the ionization potential of nitrogen. Moreover, these systems diminish in intensity as the accelerating voltage is increased above the ionizing potential; that is, as the relative number of excited neutral molecules in the emitting source decreases. The two negative systems, on the other hand, do not appear until the impacting electrons have a velocity equivalent greater than the ionizing potential. The intensity of each of these systems increases quite markedly as the voltage increases; that is, as the relative number of ionized molecules in the emitting source increases. The observed behavior, then, makes it seem quite probable that all of the systems here described, with the exception of the negative bands, are due to the neutral molecule; whereas the two remaining systems are due to the ionized molecule. These observations are in good agreement with those of other investigators in so far as experimental evidence is available. L. and E. Bloch,[1] using a three-element tube, were able to excite the second positive bands by electron impacts as low as 12 volts. Brandt,[2] using a four-element tube to investigate the ex-

[1] *Comptes Rendus*, **175**, 225, 1921. [2] *Zeitschrift für Physik*, **8**, 32, 1921.

citation limits of the nitrogen molecule due to electron impacts, obtained numerous kinks in the current-voltage curve between 7.5 and 8.2. By applying the *hr*-relation to these discontinuities he was able to construct a band which agrees in frequency difference with some of the observed positive bands. He found that the band character of these discontinuities continued beyond the ionizing potential of nitrogen, and concluded that the molecule can be ionized without dissociation. Fulcher,[1] while studying the spectra produced by low-potential discharges in air, noted that a decrease in the discharge potential was accompanied by a striking decrease in the relative intensity of the negative nitrogen bands with respect to the positive bands. Wien,[2] using the method of positive rays to determine whether certain radiations were due to charged or uncharged particles, found, in working with nitrogen, that the bands of the second positive group showed no displacement, whereas the negative bands were displaced. He concluded, therefore, that the former are due to neutral molecules whereas the latter are due to positively charged particles. Similarly, Steubing,[3] in studying the effect of electric fields on the positive-ray spectra of nitrogen, found that the intensity of the negative bands was very materially decreased with the application of strong electric fields.

Referring again to Plate I A, B, we note the behavior of the second positive and the first negative bands under varying velocities of impacting electrons. The second positive bands appear faintly at about 12 volts, increase in intensity with the voltage, reaching a maximum at about 15 volts, and then decrease with further increase in voltage; that is, they decrease in intensity as the degree of ionization in the tube increases. Figure 1 also shows the coming in of the negative band heads 4708, 4278, and 3914 at about 18 volts. This is just a little above the ionizing potential of nitrogen. These bands, also the bands of the second negative system, Plate II D, increase in intensity very markedly with increased voltage; that is, with the degree of ionization in the tube.

All of these observations support the conclusion that the systems

[1] *Astrophysical Journal*, **37**, 61, 1913.

[2] *Annalen der Physik*, **69**, 5, 325, 1922.

[3] *Zeitschrift für Physik*, **23**, 427, 1922.

designated here as positive are due to the neutral molecule, in various stages of excitation, whereas the negative bands are due to the ionized molecule.

The so-called third positive bands of nitrogen did not appear on any of the spectrograms. It is singular that any radiation due to the molecule should fail to appear when the known systems show so strongly and other systems, previously unknown, are excited. This non-appearance, then, of the third positive bands confirms the belief that they are not due to nitrogen alone but to some compound of nitrogen, probably an oxide, as is generally believed. Likewise, the absence of the cyanogen bands which have been variously attributed to the nitrogen molecule, but whose origin has been the source of much controversy, makes it appear as if they too are due to a carrier other than nitrogen. This supports the view of Barrett,[1] Rayleigh,[2] and Birge.[3]

The line spectrum of nitrogen, Plate I B*c*, only appeared for accelerating potentials above about 70 volts in moderate arcs, but could be detected as low as 35 volts in very strong arcs. This is in agreement with the observations by Compton and Duffendack[4] on the variation of the rate of clean-up of nitrogen with the voltage in low-voltage arcs. They observed a decided increase in the rate of clean-up at about 70 volts, but they also found quite an appreciable decrease in pressure in the tube when the arc was operating at potentials as low as 35 volts. This would indicate that dissociation does occur in the arc, but that the amount of dissociation is relatively slight until the impacting electrons have acquired a velocity equivalent of the order of 70 volts.

It is difficult to account for the non-appearance of the lines in moderate arcs at less than 70 volts. Apparently, it is impossible to dissociate a nitrogen molecule and ionize one of the atoms at a single impact. On the other hand, it is quite probable that there is a line emission at the lower voltages in moderate arcs corresponding to the slight amount of dissociation present, but that the emission is so faint that the lines are shaded out by the more intense band spec-

[1] *Proceedings of the Royal Society*, A, **98**, 40, 1921. [2] *Ibid.*, A, **102**, 455, 1923.

[3] *Physical Review*, **23**, 295, 1924.

[4] *Ibid.*, p. 109, 1924.

tra which extend over the greater part of the photographic plate. The lines could be photographed as low as 35 volts in very strong arcs obtained by introducing metallic magnesium into the tube.

Although the theory of band spectra is as yet far from being as firmly established as that of line spectra, there is now little room for doubt that the general method of attack which, as developed by Bohr, has proved so fruitful in the explanation of line spectra, will prove equally effective in the field of band spectra. Here, however, instead of the emission (or absorption) frequency being determined by the change in energy occurring when the atom changes from one stationary state to another as a result of the shift of an electron from one stationary orbit to another, we have a much more complicated process. Sommerfeld,[1] in his excellent treatment of the theory of band spectra, as developed by Heurlinger, Swarzschild, Lenz, and others, points out that the most general type of band spectrum may comprise several band systems of the type described in this paper. Such a band spectrum results from energy changes of three different types occurring simultaneously in molecules. Each line in a band corresponds to a particular transition in the rotational energy of the molecule, each band in a system to a given change in the vibrational energy, and finally each system is due to a specific electron transition.

We are interested here, not in the line structure of the bands, but rather in the position of the various bands that make up a system and the relations between the several systems. According to the suggestion of Heurlinger and Lenz, the different bands, usually associated in a group, are due to changes in the vibrational energy of the molecules. The nuclear vibrations are quantized just as are the molecular rotations. But, whereas at normal temperatures, the molecules of the simpler gases, as indicated by their thermodynamic behavior, do not possess appreciable vibrational energy, or, in terms of stationary states, are in their zero vibrational state, they do in general possess rotational energy.

When energy is absorbed by a gas molecule, whether it be radiant energy or energy of collision, there results in the most general case a change in the rotational and vibrational state as well as in the elec-

[1] *Atombau und Spektrallinien*, chap. vii.

tron configuration. When the molecule returns to its normal state, possibly through a series of intermediate states, it will give up this energy in the form of radiation. The frequency of the radiation emitted by any particular molecule at a particular instant is then given by the quantum-relation $\Delta E = hr$, according to the second postulate of Bohr; where now ΔE represents the difference between the energies associated with those two states of the molecule between which transition has taken place and is really the algebraic summation of the energy changes occurring simultaneously in the three transitions indicated above. The wave-number, then, of any line in a band spectrum is given by an expression of the form

$$r = F'(e', n', m') - F(e, n, m), \tag{1}$$

where e', n', and m' are quantum-numbers characterizing the initial state of the electron configuration, the nuclear vibration, and the molecular rotation, respectively, and e, n, and m are numbers characterizing the same quantities after the emission of the radiation in question. This expression when applied to the null lines, that is the lines corresponding to the rotationless states in a given band system, has been shown by Heurlinger[1] to take the form

$$r = r_e + (a'n' + b'n'^2) - (an + bn^2), \tag{2}$$

where r_e is, for the most part, the contribution to the wave-number of the emitted radiation corresponding to the change in the electronic energy and a', b', and a, b, are coefficients characteristic of the law of force between the nuclei in the initial and final states of vibration, respectively. The zero line of a band is in general not far distant from the head or edge of the band. So that, whereas the wave-number given by equation (2) corresponds strictly to the zero line of the band, it may be regarded as corresponding approximately to the band edge. Corresponding to a definite quantum-jump, n'-n, we get for different values of n' (or n) a series of bands, or zero lines that are neighbors within the same band system. These bands constitute a band group. The emission, then, of each member of a given group is associated with the same vibrational quantum-jump. Thus, for the first negative system, Plate I C and Plate II B,

[1] *Zeitschrift für Physik*, 1, 82, 1920.

the groups with heads at 3298, 3581, 3914, 4278, 4708, and 5227 correspond to vibrational quantum-shifts of $+2$, $+1$, 0, -1, -2, and -3 units, respectively. The several members of a group differ in that they are associated with different initial, and therefore different final, states of vibration. Thus, the members of the group with head at λ 4708, corresponding to a quantum-shift $n'-n=-2$, are due to quantum-shifts $0\to2$, $1\to3$, $2\to4$, etc. Bands whose emission is associated with a common initial state but with different final states of vibrational energy have wave-numbers which are related through a Deslandres progression; thus we have the several series of bands in each band system. Moreover, as Sommerfeld points out, if it happens that two electron transitions that give rise to two different band systems have either the initial state or the final state in common, these systems will be closely related. This is true of the two negative band systems described above. The fact that these two systems have the same critical potential and also the same Deslandres progression is evidence, as pointed out earlier in this paper, that they have the same initial state. Furthermore, the series relationships of the first, second, fourth, and fifth positive systems indicate that they too are associated with a common state. Birge,[1] from empirical considerations, has been led to the conclusion that the second and fourth positive bands have a common final quantum-state and that this state is also the initial state of the first positive group. In assigning quantum-numbers to the bands of these systems, he has shown that the bands with heads at λ 9108 and λ 3371 correspond to the quantum-shift $0\to0$ in the first and second positive systems, respectively. This is in good agreement with the experimental results obtained in the present investigation. Referring again to Plate II A, we note the gradual development of the second positive system as the energy of the impacting electrons is increased. It can be seen that the group with the head at λ 3371 is of maximum intensity and that the whole system develops symmetrically about this group. In fact, it appears to be generally true that the band of maximum intensity in a system is the one which corresponds to the quantum-shift $0\to0$. But, since the intensity of any particular band is proportional to the frequency of occurrence of the

[1] *Physical Review*, **23**, 294, 1924.

corresponding quantum-shift, and of the original state, we may conclude that the more probable quantum-shifts are those corresponding to the lesser values of $(n'-n)$, and in particular to the least value of n'.

It will be recalled that the first positive bands appeared first for an accelerating potential of 10 volts. However, since the o→o band at λ 9108, which should be the first of this system to be excited, was considerably beyond the range of the spectrograph used, it is quite probable that the critical potential of this system is as low as 9.5 volts. This, then, is 2.5 volts less than the critical potential found here for the second positive system. Applying the *hr*-relation to the bands λ 9108 and λ 3371, the o→o bands of the first and second system, respectively, we find that the energy associated with the radiation λ 3371 is greater than that associated with λ 9108 by an amount equivalent to 2.3 volts. This is in even better agreement with the experimental value 2.5 volts than might reasonably be expected, since, as pointed out above, the value 9.5 volts, taken as the excitation potential of the first positive system, is really an estimate based on the manner in which the various systems develop with increasing potential. An exposure at 9 volts showed no trace of these bands while at 10 volts they appeared fairly well developed.

The fact that the excitation voltage of each of the band systems photographed in this investigation is much higher than one would obtain by applying the *hr*-relation to the o→o band of the given system indicates that the molecule is not returned to the normal state by the emission of any of these systems. The absence of corresponding absorption bands in this region is in agreement with this view. In unexcited nitrogen there should be absorption corresponding to the transition of the molecule from the normal to an excited state. There is no record of absorption in the spectral region studied. According to Schumann,[1] nitrogen is very transparent even beyond λ 1650. Lyman[2] found a slight absorption extending from λ 1800 to λ 1250. In a later work[3] he extended the emission spectrum to about λ 975, where it came to an end rather sharply, suggesting the possi-

[1] *Annalen der Physik*, **6**, 418, 1901.

[2] *Spectroscopy of Extreme Ultra-Violet*, p. 63.

[3] *Astrophysical Journal*, **43**, 89, 1916.

bility of strong absorption beyond this point. It is quite obvious, then, that there must be other bands in the far ultra-violet, the emission of which corresponds to the return of the molecule to the normal state from that state in which it is left after the emission of the band systems studied here. Possibly the emission of the bands photographed by Lyman,[1] or the A bands, reported by Hopfield,[2] constitute the last stage in the return of the molecule to the normal or unexcited state.

It is to be hoped that measurements such as reported in the present paper of the amount of energy required to bring the molecule to each of the several stages of excitation corresponding to the emission of each of the several band systems may play the same important rôle in developing ideas of molecular structure and confirming the theory of band spectra as have the corresponding measurements on electron-atomic collisions in confirming and extending the general theory of atomic structure and line spectra as developed by Bohr.

SUMMARY

1. An account is given of the experimental determination of the various energy levels of the nitrogen molecule which are associated with the emission of radiation within the spectral region λλ 7000–2000. As many as six energy levels are established for the neutral molecule whereas only one, with a possibility of a second separated from the first by less than a volt, is found for the ionized molecule.

2. A study is made of the behavior of the several band systems with increasing energy of excitation, and it is shown that the development of the several systems is consistent with the present views of band spectra.

3. Arguments are presented for assigning certain band systems to the neutral molecules and others to the ionized molecule.

4. New bands in the negative band system are reported so that the system is now symmetrically developed.

5. The first, second, and fourth positive bands are shown to be due to the neutral molecule. Three new band systems, likewise due to the neutral molecule, are reported.

[1] *Spectroscopy of Extreme Ultra-Violet*, p. 113.

[2] *Physical Review*, **20**, 573, 1922.

6. A new band system is reported which is shown to have common series relationships with the negative bands of Deslandres. Each of these systems is assigned to the ionized molecule.

7. Comparison of the measured critical potentials with the voltage, as calculated by the energy equation, $Ve = hr$, corresponding to the frequency of the $0 \rightarrow 0$ band for each of the several band systems, shows that the emission of none of the band systems studied returns the molecule to the normal state, and hence leads to the prediction of a relation between these bands and a system, or systems, in the extreme ultra-violet.

8. The failure of the third positive nitrogen bands and the cyanogen bands to appear is offered as additional evidence that these bands do not belong to nitrogen.

9. It is shown that the intensity of the nitrogen line spectrum is associated with the rate of disappearance of the gas from the discharge tube and hence dependent upon the degree of dissociation.

The experimental work in connection with this investigation was carried out at the University of Michigan. The writer wishes hereby to express his gratitude to Dr. O. S. Duffendack for his many valuable suggestions and keen interest in the work; also to Professor H. M. Randall, director of the Physics Laboratory, for securing the necessary apparatus and equipment. The writer wishes, furthermore, to acknowledge indebtedness to the Palmer Physical Laboratory for the use of the large Hilger quartz spectrograph.

PENNSYLVANIA STATE COLLEGE
STATE COLLEGE, PA.
January 23, 1924

DESCRIPTION OF PLATES

PLATE I

A. The second positive bands appear first in (*b*), reach maximum intensity at about 15 volts, and then fade out with increased voltage. The three chief heads 4708, 4279, and 3914 of the negative band system appear first in (*h*) and increase in intensity with increased voltage.

B. (*a*) Those portions of the first and second positive band systems that lie within this spectral region appear fully developed at 15 volts. This spectrogram shows no trace of the negative bands. (*b*) First and second positive bands with

faint trace of line spectrum. Negative bands are here very intense. (*c*) Line spectrum here fully excited and negative bands even more intense than at 65 volts.

C. The negative groups with heads at 5227, 4708, and 4278 highly developed with seven, seven, and five bands, respectively.

PLATE II

A. (*a*) The two groups of the fifth positive system appear here at 11 volts. (*b*) The chief components of the second positive system are present at 13 volts. The weaker components of this system appear at the higher voltages.

B. The several bands and band systems labeled here are two bands with heads at 3464 and 3021, respectively; the fourth and sixth positive bands; and the first negative bands. Only the chief components of the groups are labeled.

C. Some of the members of the seventh positive system appear on this spectrogram.

D. The second negative system, of which only the chief components are labeled, is shown fairly well developed.

NOTE ON THE DISTRIBUTION AND NUMBER OF NEBULAE[1]

By FREDERICK H. SEARES

ABSTRACT

Distribution of nebulae.—A discussion of Fath's counts of nebulae on photographs of Selected Areas 1 to 139 (limiting magnitude of stars on the optical axis = 18.6, international photographic scale) shows that non-galactic nebulae make their appearance in both hemispheres at about 20° galactic latitude. They increase rapidly in frequency to 30°, and thereafter more slowly to 70°. The concentration in the region N 70°–N 90° is pronounced; the corresponding region S 70°–S 90° is not covered by the counts. For galactic latitudes 0°–70° the average surface density in the southern hemisphere (longitudes 180°–360° unobserved) is three-fourths that in the northern. The distribution in longitude is complicated, but a band of high frequency apparently crosses the northern hemisphere in longitudes 50°–220°.

Total number of nebulae.—A grouping of the counts in 39 fields for regions $10' \times 10'$ according to distance from the center of the plate shows that at $35'$ distance the loss arising from aberrations in the optical system is one-half. To reduce Fath's counts to limiting photographic magnitude 18.6 for stars at the center they must be multiplied by 1.94. The revised total number of nebulae to this limit is 210,000 for N 70°–S 70°, and about 300,000 for the whole sky.

In collecting data on the distribution of stars and nebulae I have recently had occasion to examine Fath's list of nebulae[2] compiled from photographs of the 139 Selected Areas between declinations $+90°$ and $-15°$. These photographs, forming part of the observational material for the *Mount Wilson Catalogue of Magnitudes*, are on Lumière Sigma plates, exposed one hour, the limiting magnitude ranging from about 18 to 19 on the international photographic scale. The low limit of brightness and the representative character of the Selected Areas as sample regions of the sky are features of special importance for any discussion of nebular distribution. A disadvantage, on the other hand, lies in the fact that three-eighths of the sky are wholly unobserved. For the northern galactic hemisphere the defect is not serious, but in the southern hemisphere the highest latitude observed is 76°, and, practically speaking, no plates are available for any latitude between longitudes 180° and 360°. Further, the Selected Areas are rather too widely spaced for a satisfactory determination of the effect of local irregularities in distribution;

[1] *Contributions from the Mount Wilson Observatory*, No. 297.

[2] *Astronomical Journal*, **28**, 75, 1914.

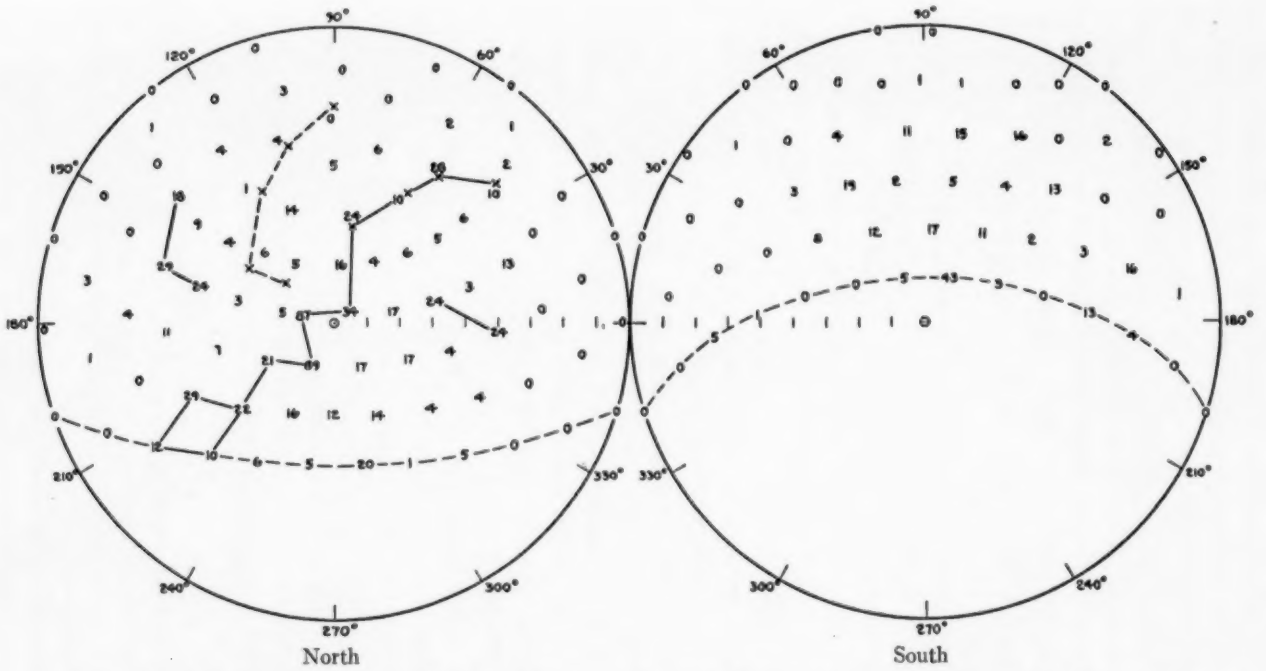


FIG. 1.—Distribution of nebulae according to Fath's counts in Selected Areas 1 to 139. The marginal numbers are galactic longitudes, the poles being at the centers of the circles.

but, in spite of these limitations, the data merit special attention because of their freedom from any selection favoring regions in which nebulae were known to exist. Sanford[1] has already discussed Fath's counts in detail from several points of view, but for the present purpose a somewhat different grouping of the material is desirable.

The numbers of nebulae counted by Fath in the 139 Selected Areas were obtained from the diagram accompanying his paper.[2] When replotted according to galactic co-ordinates[3] the distribution is that shown in Figure 1.

To illustrate the effect of local irregularities upon the mean distribution, the numbers were arranged in order of galactic latitude and divided into two series with alternate regions in each. The sums and mean latitudes for groups of five successive areas in each series are given in the first four columns of Table I and are shown graphically in Figure 2. The curves, which represent two determinations of the distribution from entirely different material, are similar, but the influence of local irregularities is obviously considerable, and a final discussion will require counts in several hundred fields. The south galactic hemisphere, and the region N 70°–N 90° in which the fluctuations in numbers are large (see Fig. 1), demand special attention.

Treated as a single series, the 139 regions in groups of five give the results in the fifth and sixth and eighth and ninth columns of Table I. These are illustrated in Figure 3, in which the curves for northern and southern galactic latitudes are shown side by side. The seventh and the last columns of the table give the average limiting photographic magnitudes to which star-counts in fields 23′ in diameter on the same series of photographs are complete.[4] Since the variation in the limit, which ranges from 17.8 to 18.6, is not closely correlated with the irregularities of the curves in Figure 3, the mean distribution cannot be seriously influenced by the lack of constancy in the limit.

[1] *Lick Observatory Bulletins*, **9**, 80, 1917.

[2] *Loc. cit.* The total thus found is 1032 and is that used here, although Fath's tables give a total of 1031. The difference is unimportant and is mentioned only in explanation of its origin.

[3] Taken from *Harvard Annals*, **101**, Table II, 1918; **102**, Table I, 1923.

[4] Unpublished data from the *Mount Wilson Catalogue of Selected Areas*.

Owing to the comparative rarity of diffuse nebulae and planetaries, Fath's list is practically one of non-galactic nebulae, with the

TABLE I

DISTRIBUTION OF NEBULAE IN GALACTIC LATITUDE
(Observed numbers for areas of 9.4 sq. deg.)

SERIES I		SERIES II		ADOPTED GROUPING					
Lat.	No.	Lat.	No.	Lat.	No.	Mag.	Lat.	No.	Mag.
+75°....	149	+72°	146	+78°	232	18.3	+12°	0	18.4
60....	69	59	60	69	63	17.9	+ 6	2	18.2
50....	53	49	42	62	54	18.3	0	0*	18.1
42....	60	41	45	58	75	17.9	0	0	18.2
34....	99	33	25	52	48	17.9	− 6	0	18.3
26....	26	26	4	48	47	17.8	12	4	18.4
17....	8	16	3	43	33	17.8	14	1	17.8
+ 9....	1	+ 8	1	40	72	18.4	20	1	18.3
0....	0	0	0*	36	69	18.3	25	25	18.0
− 9....	1	− 9	3	31	55	17.8	31	59	18.6
16....	1	18	1	28	18	18.1	38	20	18.3
27....	24	29	60	24	12	18.0	45	32	18.2
40....	28	43	24	19	7	17.9	54	31	17.9
−60....	66	−63	33	+14	4	17.9	−69	68	18.4

* Four areas. All other groups include five each.

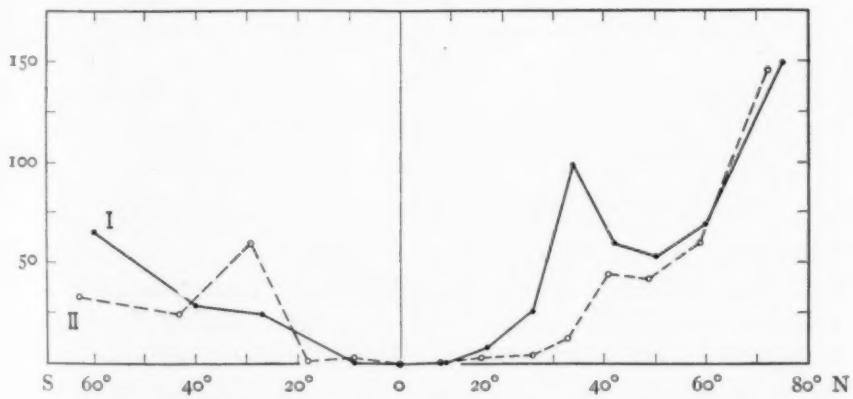


FIG. 2.—Distribution of nebulae in galactic latitude. Curves I and II represent results derived from alternate regions in the sequence of 139 Selected Areas arranged according to galactic latitude. They illustrate the influence of irregularities in distribution.

small elliptical nebulae greatly predominating over the spirals. Figure 3 shows that the non-galactic nebulae appear at about lati-

tude 20° and rapidly increase in frequency to 30°. From 30° to 70° the increase is slow, but the concentration near the north galactic pole at least is pronounced. The systematic difference between the northern and southern hemispheres seems to be real.[1]

To gain some notion of the distribution in galactic longitude, the fifty-four regions between 20° and 68° north latitude were divided into four zones: 20°–29°, 30°–39°, 40°–49°, 50°–68°. Plots of numbers

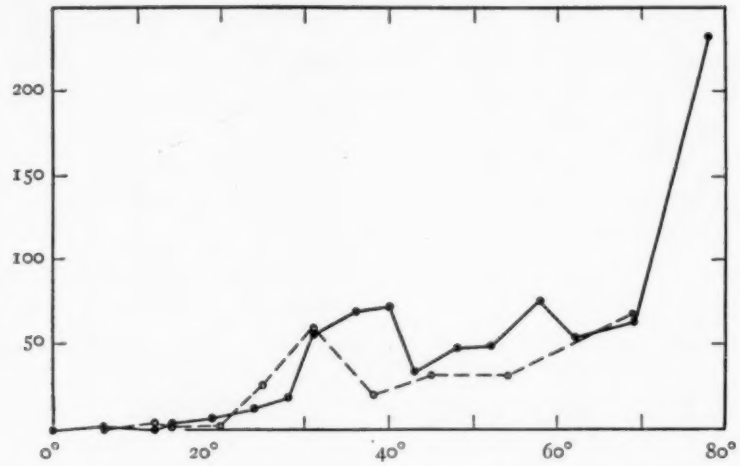


FIG. 3.—Distribution according to galactic latitude of nebulae in Selected Areas 1 to 139. Full line, northern hemisphere; dotted, southern hemisphere. Ordinates are numbers counted in areas of 9.4 sq. deg.

of nebulae against longitude for these zones are shown in Figure 4. The series of maxima marked *A* and *B* suggest something more than local irregularities of distribution; but since Figure 1 indicates a minimum for the second curve at about 180°, the maxima *C* are perhaps of more significance than *B*. The distribution of rich fields as shown in Figure 1 seems to justify the assumption, for the most striking feature appears to be a band of high frequency crossing the northern hemisphere near the pole, in longitudes 50°–220°. The minimum starting in low latitudes at longitude 90° is clearly marked and penetrates almost to the pole itself. Figure 1 bears no close relation

[1] In this connection see Reynolds' diagrams, *Monthly Notices, R.A.S.*, **81**, 129, 1920; **83**, 147, 1923; **84**, 76, 1923.

to the diagrams of Reynolds,[1] but it must be remembered that the great majority of the nebulae in Fath's list are much smaller than those discussed by Reynolds, nearly all of them having diameters under 30″. Apparently we have here a further illustration of what is shown by Reynolds' data, namely, that the distribution in longitude varies with the size of the nebulae.

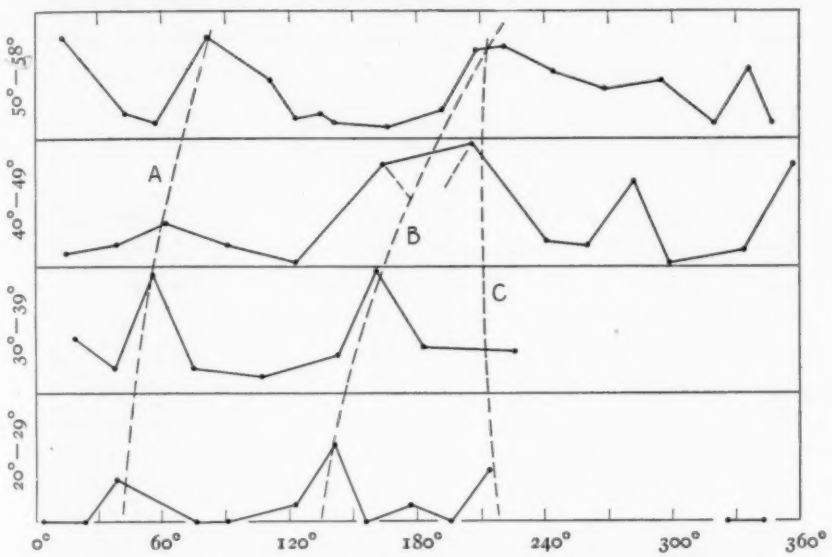


FIG. 4.—Distribution of nebulae in north galactic hemisphere according to galactic longitude (abscissae). Four curves for the latitude intervals noted in the margin. *A*, *B*, *C* are more-or-less hypothetical lines of maximum frequency. *A* and *C* correspond to the maximum in longitudes 50°–220° shown in Fig. 1.

There remains still the question of the total number of nebulae in the sky, concerning which there has been much difference of opinion. Fath's estimate of 162,000[2] differs widely from Perrine's earlier result of 500,000,[3] and still more widely from Curtis' 722,000.[4] Perrine,[5] allowing for a selection of fields favoring rich regions, subsequently reduced his estimate to 400,000; but Curtis' estimate,

[1] *Loc. cit.*

[2] *Loc. cit.*

[3] *Lick Observatory Bulletins*, **3**, 47, 1904.

[4] *Publications Lick Observatory*, **13**, 15, 1918.

[5] *Astronomical Journal*, **29**, 79, 1916.

which like that of Perrine is based on photographs taken with the Crossley reflector, still stands. The limiting magnitude of the Crossley photographs is undetermined, but it has usually been assumed that it is nearly the same as that of the Mount Wilson plates. In fact, the circumstances of plates, telescopes, and exposure times, supplemented by direct comparisons, seem to warrant the assumption of direct comparability. To account for the discrepancy, Fath suggested that the regions photographed with the Crossley reflector are not representative. Perrine and Curtis, on the other hand, have insisted that Fath's total is too small because of losses arising from aberrations in the relatively large field used by him (about $72' \times 95'$).

The limiting magnitude of the Mount Wilson photographs is now known. The mean for star-counts which are complete, from the data in Table I, is 18.1, photographic scale, while the mean for the faintest stars recorded, that is, the actual limiting magnitude at the center of the plate, is about 18.6. The question of aberration losses can be settled from the data themselves, and since, as far as they go, there can be no question as to the representative character of the Selected Areas, an estimate of the total number of nebulae to a specified limit of brightness, correct within a moderate percentage, should now be possible.

The first step in arriving at such an estimate is the determination of a factor for the correction of Fath's numbers for aberration losses, which do seriously affect his total. This factor has been based on counts in unit areas $10' \times 10'$ in each of the regions showing a total of ten or more nebulae (thirty-nine Selected Areas in all). The counts, which were made by Miss Joyner from Fath's list, were in all cases between $10'$ values of the declination. As a matter of convenience it was assumed that the optical axis was always located either on the edge or at the middle of a $10'$ zone, the choice in any given case being determined by the declination of the central star of the area, on which the plate was centered. This choice also fixed automatically the limits in right ascension, which were so placed that the adopted center coincided either with the corner or with the center of a $10' \times 10'$ area. In the former case the total area counted was $60' \times 60'$; for the latter it was $70' \times 70'$. This selection

of unit areas simplified the counting, and since the average displacement of the adopted center from the true optical center is less than 2′, the precision is ample.

The results were divided into six groups (fields 60′×60′, groups I–III; 70′×70′, groups IV–VI), each group including several Selected Areas and a total of about one hundred counted nebulae. The counts within each group were summed for corresponding 10′×10′ areas, thus giving a frequency diagram showing the variation in

TABLE II

CORRECTION FACTOR FOR FATH'S COUNTS OF NEBULAE

Dist.	60′×60′, Standard Total=100					Dist.	70′×70′, Standard Total=123				
	I	II	III	Mean	Wt.		IV	V	VI	Mean	Wt.
7′	3.7	5.2	3.8	4.2	4	0′	4.1	5.8	1.4	3.8	1
16	2.8	2.5	3.1	2.8	8	10	4.1	2.3	4.1	3.5	4
21	2.8	3.6	4.5	3.6	4	14	3.2	2.3	3.0	2.8	4
25	2.2	2.4	2.7	2.4	8	20	2.6	5.5	3.3	3.8	4
29	2.7	2.4	1.9	2.3	8	22	3.7	3.3	1.4	2.8	8
35	3.2	1.4	1.4	2.0	4	28	2.5	2.1	3.0	2.5	4
						30	3.4	2.1	2.0	2.5	4
						32	1.1	2.1	3.0	2.1	8
						36	1.2	2.1	2.8	2.0	8
						42	1.7	0.6	0.6	1.0	4
No. S.A.	5	7	11	23	.....	.....	2	6	8	16	.....
No. Fath.	159	143	140	442	.....	.....	176	124	106	406	.....
No. counted.	108	105	106	319	.....	.....	152	107	92	351	.....
Corr. no.	293	285	287	.....	.....	.....	336	236	203	.....	.....
Corr./Fath.	1.84	1.99	2.05	.....	.....	.....	1.91	1.91	1.92	.....	.....

the number of nebulae with increasing distance from the adopted center.

The average densities (numbers of nebulae per 10′×10′ area) found from these diagrams for each group, reduced to standard totals for the whole area counted to make them directly comparable, are given in Table II under the headings I–VI. The standard totals used are 100 and 123; the latter, referring to regions 70′×70′, was determined by the condition that the total for the central 60′×60′ region in an area 70′×70′ should be 100. The weights in the sixth and last columns of Table II are the numbers of unit areas per field upon which the different densities are based.

All the groups show a decrease in density with increasing dis-

tance. The means for groups I–III and IV–VI, plotted in Figure 5 as points and crosses, respectively, agree well and show that the influence of irregularities and clustering have been rather thoroughly eliminated. The loss in density with increasing distance is so large that at 35′ from the center the number of nebulae recorded is only one-half that at the center.

The central density, which may be taken as 4.0, determines the true number of nebulae per square degree corresponding to an observed total of 100. The result is $4.0 \times 36 = 144$, or 271 for 1.88 square

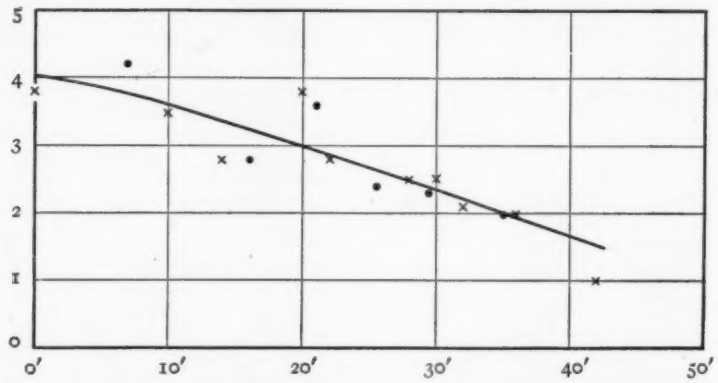


FIG. 5.—Decrease in number of nebulae counted (ordinates) with increasing distance from center of plate (abscissae). Points and crosses are mean results for groups I–III and IV–VI, respectively, including 670 nebulae in 39 Selected Areas photographed with the 60-inch reflector. Ordinates refer to a unit area of 10′×10′ and have been reduced to a standard counted total of 100 in a field 60′×60′ centered on the optical axis.

degrees, which is the field of the original photographs. The numbers of nebulae counted by Fath are given in the fourth line from the last of Table II, while the numbers counted for the present discussion are in the next line. The corrected number per 1.88 square degrees in any given case is

$$\text{Corr. No.} = 271 \times \text{No. Counted/Standard No.}$$

The reduction factor for Fath's counts is therefore the ratio Corr. No./Fath's No.

The close accordance of the results in the last line of Table II

shows that the various groups are mutually consistent and little affected by irregularities in the distribution. The adopted mean factor is 1.94. The principal source of uncertainty affecting this result is in the density adopted for the center of the field, namely, 4.0. An inspection of Figure 5 indicates that this may be in error by as much as 5 or 10 per cent, the error being carried over into the correction factor practically unchanged, and hence also into the estimate of the total number of nebulae in the sky.

TABLE III

MEAN DISTRIBUTION IN GALACTIC LATITUDE AND TOTAL NUMBER OF NEBULAE TO PHOT. MAG. 18.6

LATITUDE	UNCORRECTED NO. 9.4 SQ. DEG.		CORRECTED NO. 1 SQ. DEG.		AREA OF ZONE	TOTALS IN THOUSANDS	
	N.	S.	N.	S.	Sq. Deg.	N.	S.
0°–10°	1	0	0.2	0.0	3580	0.7	0.0
10–20	4	2	0.8	0.4	3474	2.8	1.4
20–30	12	26	2.5	5.4	3259	8.1	17.6
30–40	64	40	13.2	8.2	2945	38.8	24.2
40–50	50	28	10.3	5.8	2541	26.2	14.7
50–60	59	34	12.2	7.0	2063	25.2	14.4
60–70	59	58	12.2	11.9	1520	18.5	18.1
70–80	150	.....	31	.....	930	28.8	(21.6)
80–90	(330)	.....	(68)	.....	314	(21.4)	(16.0)
Totals 0°–70°						120.3	90.4
Totals 70–90						(50.2)	(37.6)
Totals 0–90						170.5	128.0

Total N 70° to S 70°, 210,000; whole sky, 300,000.

This estimate can now be made with the aid of the data in the sixth and ninth columns of Table I, which lead to the averages for 10° zones of galactic latitude given in the second and third columns of Table III. The area to which these numbers refer is $5 \times 1.88 = 9.4$ square degrees. The numbers of nebulae per square degree, corrected for aberration losses, are found by multiplying by $1.94/9.4 = 0.206$. The results in the fourth and fifth columns of Table III are the final values for the distribution in galactic latitude. To 70° in the northern hemisphere no great change is to be expected as a result of future counts. The values for the region about the north galactic pole, 70°–90°, are uncertain, and all the densities for the

southern hemisphere are subject to considerable revision because of the unsymmetrical distribution of the photographs.

The summation for the different zones given in the last two columns of Table III indicates that the mean density for southern latitudes is about three-fourths that for northern latitudes. The numbers adopted for the region S 70°–S 90° are assigned on the basis of the rather risky assumption that this ratio holds for all latitudes. Unless the unobserved part of the southern hemisphere is quite different from the observed portion in its number of nebulae, a round total of 210,000 from N 70° to S 70° should not be seriously in error. The estimate of 300,000 for the whole sky is much less reliable; but with all reasonable allowance for deficiencies and uncertainties, this result cannot be directly reconciled with the much larger estimate of Curtis. Either the limiting magnitudes of the two series of photographs have not the equality hitherto supposed, or else the observed regions which are the basis of the larger estimate are not representative of the sky as a whole.

MOUNT WILSON OBSERVATORY
June 1925

METHODS USED IN STELLAR PHOTOGRAPHIC PHOTOMETRY AT THE YERKES OBSERVATORY BETWEEN 1914 AND 1924

By J. A. PARKHURST[1] and ALICE H. FARNSWORTH

ABSTRACT

Plates taken in focus gave photographic magnitudes on ordinary Seed plates without color-filter, and photovisual magnitudes on Cramer Isochromatic plates behind yellow filters. Parallel-wire objective gratings gave the scale independently on each plate by comparison of the central image with the first-order spectra. The magnitudes were expressed in the International System either by direct comparison with the North Polar Sequence or indirectly by the use of the Potsdam photometric *Durchmusterung* and a spectral classification found from objective-prism plates.

Most of the topics given below are treated in greater detail by Miss Farnsworth in her doctor's thesis entitled "Comparison of the Photometric Fields of the 6-Inch Doublet, 24-Inch Reflector and 40-Inch Refractor," submitted in 1920, which will appear in a future volume of the *Publications of the Yerkes Observatory*.

INSTRUMENTS

The instruments used are described in Table I:

TABLE I

Desig.	Type		Form	Aperture			Focal Length		Scale 1 mm=
				Full	Used				
				in.	mm	in.	in.	mm	
UV....	Refractor	Photog.	Petzval doublet	5.7	145	4	32	814	253″
R.....	Reflector	Achrom.	Newtonian	23.5	597	12.18	93	2360	87.4
40-inch	Refractor	Visual	Clark	40	1016	40	744	19340	10.66

The comparison between the results with the different instruments was considered of as much importance as the results themselves, on account of the mutual checks and a demonstration of the possibilities and limitations of each. The series of plates taken with these telescopes are called "UV," "R," and "O," respectively; the first named from the Jena "ultra-violet" glass forming the lenses

[1] Died March 1, 1925.

and objective prisms, which transmits 50 per cent of the incident light at wave-length 3050 through 1 cm of glass.

PLATES AND FILTERS

Photographic magnitudes have been found principally on Seed 30 plates, sensitive in the blue region. Photovisual magnitudes are obtained from Cramer Isochromatic plates, both instantaneous and medium, which were found to have similar curves of sensitiveness when used behind a yellow filter.

The limits of transmission given in column 6 of Table II apply to the combination of plate and filter used, and give an indication of the spectral range of the light strong enough to affect the plate with

TABLE II

FILTERS

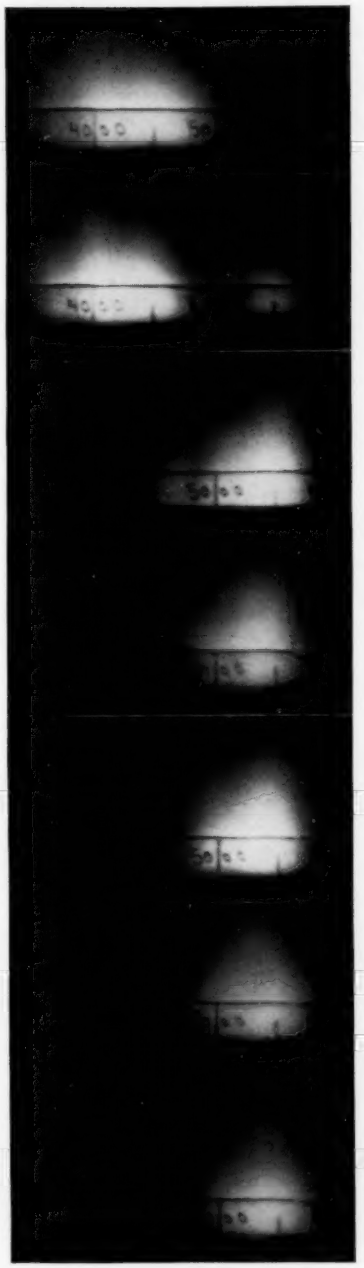
SERIES	FILTER	SIZE IN INCHES	KIND	MAKER	TRANSMISSION	USED	
						From	To
					A		
UV.....	Beta 10	4×5	Gelatine	Wallace	5000–6000	1907 Feb. 20	1924
R.....	Beta 7	3×3	Gelatine	Wallace	4800–6000	1906 July 24	1914 Sept. 30
R.....	W 12	3×3	Gelatine	Wratten	5000–6000	1914 Sept. 30	1917 July 9
R.....	J1	3×3	Colored glass	Schott	4800–5900	1917 July 9	1924
O.....	Dec.,'07	8×10	Gelatine	Wallace	4900–6000	1907 Dec. 15	1920 June 2
O.....	M 1	8×10	Gelatine	Mees	4900–6000	1920 June 5	1924

moderate exposures. This is a fundamental point in the determination of photovisual magnitudes and color-indices, and has not usually been specifically given in publications of such magnitudes and colors. Plate III shows the spectral sensitivity of the combinations of plate and filter used, as recorded by a Wallace spectrograph provided with a transmission grating and a rotating sector before the wide slit.

MEASUREMENT

The plates were measured by the aid of an artificial scale formed by making on a star exposures changing in a logarithmic ratio, thus forming a row of images with approximately equal intervals in magnitude. These scales were made in and for each telescope and in different conditions of seeing to match similar conditions in the plates to be measured. The plates were placed on the table, *L*, of a

PLATE III



SPECTRAL INTENSITY OF COMBINATIONS OF PLATE AND FILTER

Hartmann microphotometer (Fig. 1). An incandescent lamp, *l*, illuminates both plate and scale, the images being united in the Lummer-Brodhun cube. The silvered lower half of the cube reflects the plate-images, and the clear upper half transmits the scale-images into the ocular *A*. The scale is moved by the pinion *P* until an image, *a*, brighter than the star to be measured, *S*, appears at the left, and a fainter image, *b*, at the right. The interval *aS* is then estimated in tenths of the interval *ab*.

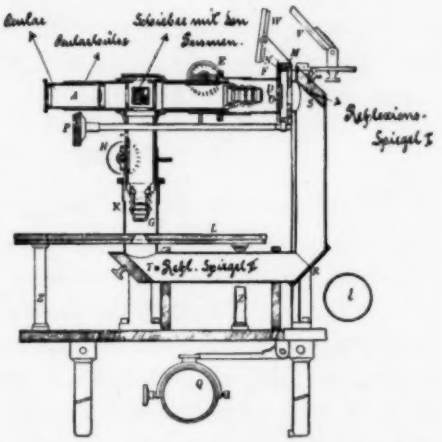


FIG. 1.—Diagram of Hartmann Microphotometer.

The ratios of the exposure-times for the artificial scales were the square roots of 2, 3, and 4. The value of the intervals between scale-images is about half a magnitude, varying from plate to plate according to the contrast and the quality of the images. The estimates are thus in units of about 0.05 mag. and the mean of two to four estimates gives a precision of measurement somewhat better than 0.05 mag. for a single good image.

CALIBRATION OF THE FIELD

The general method for the calibration of the field for the determination of corrections to reduce all images to the optical axis was the same for the three instruments, though each offered its special problems in working out the details. Polar stars, usually Polaris, Harvard Polar Sequence Number 5, and B.D.+88°5 (magnitudes roughly, 2, 6, and 9), were moved across the optical axis by the slow motion in declination, forming rows of images with equal exposures at different distances, *r*, from the axis. Measurement of these rows with the artificial scales gave calibration-curves, yielding a table of corrections by which any image could be reduced to the size it would have if it had been on the axis. It was found that the

corrections, expressed in terms of the scale-readings, were functions of the intensity of the image as well as its distance from the axis. A large image would increase in size with distance r, while a small image would decrease, and an image of some intermediate size would show little change. This follows from the character of the photographic images obtained with any one of the three instruments, but the details of the calibration-curves and the tables of corrections vary greatly from one instrument to another, as might be expected from their diverse characteristics. The field of the reflector is the simplest and will be described first.

FIELD OF THE 24-INCH REFLECTOR

The plates were focused sharply by a knife-edge (the Foucault method) for a star on the axis; all other positions on the plate being therefore outside the focal surface, and the corresponding images, if strong enough, being larger than those on the axis. From 26 plates having 416 exposures the best 49 rows were used to determine the corrections with apertures of 12 and 18 inches; and, for each aperture, on Seed 30 plates without filter, and on Cramer Isochromatic plates with filter Beta 7 or J1, yielding, respectively, photographic and photovisual magnitudes. Figure 2 shows specimen curves of the four varieties, plotted with distances, r, from the axis as abscissae, and mean scale-readings, S, as ordinates. The larger images have the smaller scale-readings for convenience in reduction to magnitudes. Only one branch of each of the curves is plotted, as they are symmetrical with respect to the axis. It will be seen that the shape and slope of the curves vary decidedly with the size, S, of the image, also that the slope is less on the plates taken through the yellow filter, and less with 12-inch than with 18-inch aperture.

These curves contain all the data needed for the corrections; it only remains to tabulate them in a double-entry table with arguments S and r. In practice this was accomplished by the aid of two intermediate tables and sets of curves, the details of which it is not necessary to give here.

Table III gives, as a specimen, part of the corrections used for Cramer (photovisual) plates with 18-inch aperture, as measured with artificial scale R5. It will be noticed that the positive correc-

tions increase with values of r for the larger images, but between scale-readings 8 and 9 the slope changes and the more distant images have negative corrections.

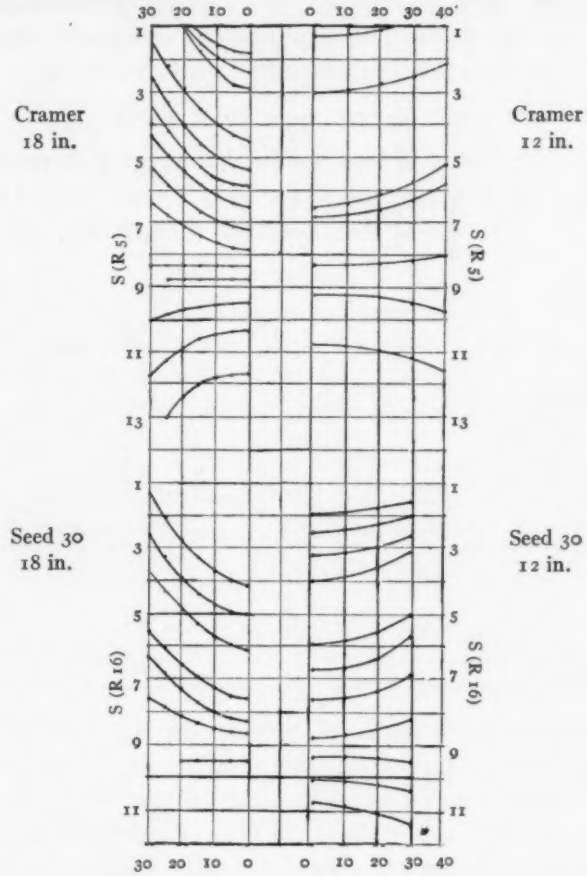


FIG. 2.—Preliminary Curves. Reflector

As can be inferred from Figure 2, the corrections for Seed 30 (photographic) plates taken with 18-inch aperture are a trifle larger than the quantities in Table III for the larger images having positive corrections. For the values of S greater than 10, the images are not well enough defined to permit of measurement. For the Seed 30 plates taken with 12-inch aperture the corrections are less than in Table III, and the smaller images permit measurement and have

negative corrections. The same applies in greater degree to the Cramer 12-inch plates.

The Cramer plates taken with the yellow filters and 12-inch aperture permit of measurement to 40′ (28 mm) from the axis. The other combinations permit of measurement out to 30′, though the Seed 30 plates with 18 inches are better restricted to 25′.

FIELD OF THE ZEISS UV CAMERA

This field is peculiar in that the focal setting for sharpest images on the axis varies with the size of the image on account of the over-correction of the lens and the character of the coma. As usual in

TABLE III

R PHOTOVISUAL CORRECTIONS

(For 18-in. aperture, expressed in terms of scale-readings)

$S(R_5)$ \ r	2′	4′	6′	8′	10′	12′	14′	16′	18′	20′	22′	24′
1.0	+0.06	+0.15	+0.26	+0.42	+0.60	+0.83	+1.07	+1.34	+1.62	+1.88	+2.15	+2.41
2.0	+ .05	+ .13	+ .24	+ .38	+ .54	+ .75	+0.97	+1.21	+1.45	+1.70	+1.95	+2.20
3.0	+ .05	+ .11	+ .22	+ .35	+ .51	+ .70	+ .91	+1.13	+1.34	+1.55	+1.77	+1.99
4.0	+ .04	+ .11	+ .20	+ .32	+ .45	+ .63	+ .80	+1.00	+1.18	+1.38	+1.58	+1.77
5.0	+ .03	+ .09	+ .17	+ .28	+ .41	+ .55	+ .70	+0.85	+1.02	+1.18	+1.36	+1.51
6.0	+ .03	+ .08	+ .15	+ .23	+ .34	+ .46	+ .58	+ .71	+0.84	+0.97	+1.10	+1.23
7.0	+ .02	+ .06	+ .12	+ .18	+ .26	+ .35	+ .43	+ .52	+ .60	+ .70	+0.80	+0.90
8.0	+ .02	+ .03	+ .06	+ .08	+ .12	+ .15	+ .18	+ .22	+ .27	+ .32	+ .37	+ .42
9.0	.00	− .01	− .02	− .03	− .04	− .05	− .06	− .08	− .09	− .12	− .14	− .17
10.0	.00	− .02	− .03	− .07	− .10	− .14	− .19	− .25	− .30	− .36	− .43	− .50
11.0	.00	− .02	− .03	− .07	− .10	− .17	− .24	− .33	− .42	− .53	− .65	−0.77
12.0	0.00	−0.02	−0.03	−0.07	−0.10	−0.17	−0.26	−0.37	−0.50	−0.65	−0.83	−1.00

the use of a doublet lens, the plate was placed inside (in this case about a half-millimeter) the position of the plane tangent to the focal surface for images of medium size, so that these images were sharpest between 1° and 3° from the axis. Calibration plates taken on polar stars gave correction-curves similar to those for the reflector, but peculiar in the values of r for the sharpest images. Figure 3 illustrates these peculiarities, especially marked for the photographic (Seed 30) plates. Curve *a* shows the value of r for the best focus of a large image to be 2°.2; curve *b* for a medium image, 1°.9, while curve *c* shows a small image in best focus on the axis. On the photovisual plates taken through the yellow filter, these peculiarities are present, but less marked since the filter suppresses part of the coma.

As a result of these conditions it was necessary to focus with

great care. The knife-edge method could not be used since the bright stars were not in focus on the axis. After many experiments a system of focal settings was devised, depending on the temperature, which gave a consistent set of correction-curves. This system was checked by means of "spectral distances" on plates taken with the

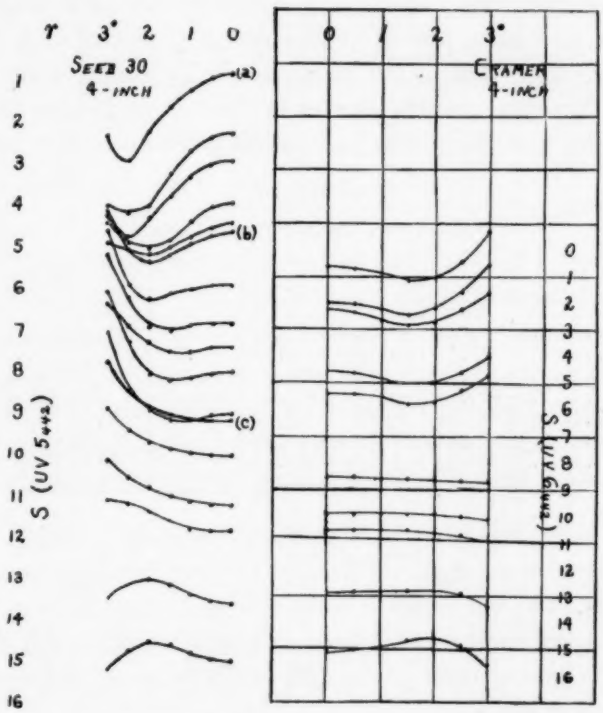


FIG. 3.—Preliminary Curves. 6-inch Doublet

objective grating R6. This gives spectra of the first order about 0.4 mm in length, and permits precise measurement of the distance between the central image and the position of best focus in the spectrum. This distance increases about 0.01 mm for an increase of 0.03 mm in the focal setting and thus furnishes a good check on that setting.

Table IV gives in a condensed form the corrections to be applied to the UV photographic plates, in terms of the scale-reading with the artificial scale 5_{442}.

FIELD OF THE 40-INCH REFRACTOR

On the 8×10 plates used, the field did not extend beyond 25′ from the axis. Within this field the distortions were of moderate size and presented no peculiarities. The only difficulty in finding the corrections arose from the rapid changes in the character of the images due to varying conditions of seeing, so that it was usually impossible to take a row of images across the plate with uniform conditions. This difficulty was overcome by taking rows on rich fields like Praesepe and the cluster in Perseus, and, from the abundance of data on the plates, determining the correction necessary

TABLE IV

UV PHOTOGRAPHIC CORRECTIONS

S_s \ r	0°.5	1°.0	1°.5	2°.0	2°.5	3°.0
0.0.....	−0.14	−0.52	−0.99	−2.08	.....	.....
2.0.....	− .13	− .42	− .94	−1.87	.....	.....
4.0.....	− .11	− .31	− .81	−1.44	−1.87	.....
6.0.....	− .08	− .20	− .45	−0.46	+0.09	.....
8.0.....	− .04	− .08	− .04	+ .09	+ .52	.....
10.0.....	+ .02	+ .06	+ .15	+ .28	+ .63	+1.02
12.0.....	+0.04	+0.13	+0.32	+0.54	+0.62	+0.60

to reduce each exposure to an average condition of seeing. Tables of corrections were deduced from 110 rows of images on 4 of the best plates. The values for faint images quite distant from the axis were afterward improved by data derived from 115 spectral images made with the objective grating on 15 plates of the Kapteyn areas at declination +45.°

DETERMINATION OF PHOTOMETRIC SCALE

The reduction of differences in scale-reading to differences in magnitude was accomplished by the aid of parallel-wire gratings placed over the objectives of the refractors and over the open end of the tube of the reflector. By the laws of diffraction[1] we know the proportion of the incident light going into the central (undiffracted) image and into the spectra of the various orders, and their relations can be expressed in magnitudes.

[1] See Alice H. Farnsworth, "An Elementary View of Diffraction as Applied to Photographic Photometry," *Popular Astronomy*, **28**, 326–33 and 458–69, 1920.

The design of a grating to give best results with a given telescope and with plates sensitive to a given range of wave-length depends on two factors: (1) The pitch (sum of the clear and opaque space) of the grating determines the separation of central and spectral images; (2) the ratio between the clear and opaque space determines the proportion of light going into the central and spectral images. In

TABLE V

PHOTOVISUAL CORRECTIONS FOR 40-INCH PLATES

S_{23} \ r	5′	10′	15′	20′	25′
2.0	+0.02	+0.09	+0.21	+0.41	+0.70
4.0	.00	+ .06	+ .19	+ .36	+ .60
6.0	.00	+ .05	+ .15	+ .31	+ .47
8.0	.00	+ .03	+ .10	+ .16	+ .23
10.0	.00	− .04	− .09	− .15	− .22
12.0	−0.10	−0.17	−0.30	−0.42	−0.50

practice the separation of images should be as small as possible without overlapping, for then the spectra may be round and measurable as star-images. The ratio between clear and opaque space should be such as to give suitable differences in magnitude between a free image (taken without grating) and the central and spectral

TABLE VI

PHOTOMETRIC GRATINGS

Tel.	Name	Aper.	No. of Rods	a	d	$\frac{a}{a+d}$	$D(ph)$	$D(pv)$	Abs. $c-f$	Int. $s-c$
		in.		mm	mm		mm	mm	M	M
UV	R6	4	401	0.124	0.129	0.490	1.32	1.80	1.57	(0.92)
UV	R8	4	52	1.039	1.013	.507	0.16	0.22	1.50	0.98
UV	R9	4	32	2.281	0.923	.712	.10	.14	0.74	2.26
UV	P10	4	28	1.715	1.766	.493	.10	.13	1.53	0.95
R	P7	17.5	56	3.87	3.93	.496	.12	.17	1.50	0.99
R	P7b	17.5	21	3.87	3.93	.496	.12	.17	(0.35)	3.33
R	P7b	12	21	3.87	3.93	.496	.12	.17	(0.53)	2.80
40	P5	40	40	12.3	12.7	.491	.32	.45	(1.53)	0.95
40	P6	40	23	12.3	12.7	0.491	0.32	0.45	(0.78)	2.38

images with the grating. If these differences in magnitude are too small they will not give precise photometric scales; if too large they will unduly reduce the number of stars on a given plate which will have measurable images both central and spectral. Extended experiments finally pointed out the gratings listed in Table VI as best adapted to the three telescopes.

In Table VI the first four columns explain themselves; a and d represent the width of free space and diameter of the rods; the quantity $\frac{a}{a+d}$ is plotted in Figure 4; $D(ph)$ and $D(pv)$ are the distances between centers of central and first-order spectral images for photographic and photovisual rays; Abs. c–f is the absorption of the grating, that is, the reduction in magnitude of the central

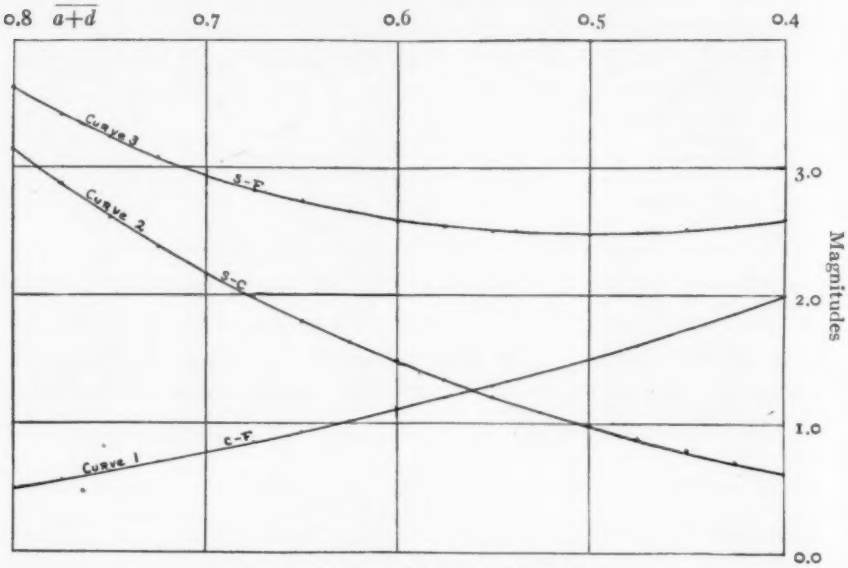


FIG. 4.—Effect of Objective Grating

image as compared with a free image without the grating; Int. s–c is the interval in magnitude between central image and first-order spectrum, *the quantity used in practice for the determination of relative magnitude.*

Figure 4 shows the effect of the objective grating. The abscissae are values of the fraction $\frac{a}{a+d}$, and the ordinates are differences in magnitude. Separate curves are drawn for the difference between free and central (curve 1), between central and spectral (curve 2), and between their sum, free and spectral (curve 3). This figure is inserted to show the advantage of the grating for which $\frac{a}{a+d}=0.5$

(which we have called a "normal grating"), since the difference s–f (2.48 mag.) is well known even if an error as large as 10 per cent is made in measuring the ratio $\frac{a}{a+d}$. Hertzsprung[1] called attention to this property and suggested its use in fixing the value of the interval s–c. We have accordingly used it for the three gratings UV, R9; R, P7b; and 40, P6. The last two were "normal" gratings from which the exterior rods were removed, leaving a central group. The effect of this removal was to increase the value of the interval s–c from 0.98 to 2.80 and 2.38 mag., respectively. If the grating which is to be tested be called "new," the exposures are made in the order, new, normal, free, normal, new. The measured interval s (normal) *minus* free then fixes the scale of the plate, and the value of s–c in the "new" grating can be expressed in magnitudes. In this way the values in the last column in Table VI were found for the three gratings in question, these values being checked by the measured dimensions of the gratings.

It only remains to transform the measured intervals in scale-reading, S, on a given exposure, to intervals in magnitude by means of this known value of s–c. Since the exposures for the artificial scales were in logarithmic ratio, the intervals between the adjacent scale-images (i.e., the values of the scale-unit) should be constant when expressed in magnitudes. This is true in practice when the contrast on the negative and the scale-plate is the same. By choosing a scale to match the plate, the differences in S between spectral and central images for bright and faint stars are usually free from systematic runs, and the mean value of a scale-unit expressed in magnitudes is found by dividing the known difference in magnitude, s–c, by the corresponding difference in scale-reading, so that $dM/dS = S'$. If each scale-reading (corrected for distance of the star from the axis, from the calibration tables) is multiplied by S', the products will represent the relative magnitudes of the measured images. For some plates, on account of conditions of exposure or development, a systematic run is shown in the values of dS for bright and faint stars. Then the reduction is not so simple, and we have followed the

[1] *Astronomische Nachrichten*, **186**, 177, 1910.

method suggested by Miss Leavitt,[1] which is in substance the common method of calibrating any scale.

ZERO-POINTS

As this paper deals only with general methods it is not the place for details in regard to the manner of expressing the results on the International Scale of magnitudes. Suffice it to say that direct comparisons with the North Polar Sequence by duplicate exposures on the plate in the order, field, pole, field, were found to introduce considerable uncertainty from local differences in transparency or change in conditions between exposures. The wide field of the UV camera, 6° or more, usually made it possible to include on the plate some stars found in the Potsdam or Harvard visual catalogues. The visual data could be reduced to photographic magnitudes by correcting for color-index from the spectral classification found on our objective-prism plates. The results from this indirect method were usually more accordant than from direct comparisons with the pole.

COLOR-EQUATION

The use of three different instruments called for and received careful comparison of color-values. As was expected, no perceptible difference was found in the photovisual results between reflector and refractors; but it was an unexpected result when the difference in photographic magnitudes between the UV camera and the reflector proved to be very near to zero. This is evidently due to the unusual transparency of the UV glass in the ultra-violet. The two kinds of instruments used here therefore occupy a position intermediate between those at Mount Wilson where Seares[2] found that the lens absorbed more of the ultra-violet light than the mirror, and those at Harvard where King[3] found that the mirror absorbed more than the lens.

YERKES OBSERVATORY AND
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January 1925

[1] *Harvard Annals*, **71**, 147. See also S. W. Holman, *American Journal of Science*, **132**, 278, 1882.

[2] *Astrophysical Journal*, **56**, 87, 1922. [3] *Harvard Annals*, **76**, 188, 1915.

ON THE CAUSE OF STAR-STREAMING

By BERTIL LINDBLAD

ABSTRACT

Assuming tentatively a law for the velocity-distribution in the big stellar universe, the possibility of radial stream-motions due to encounters of stars with vast local accumulations of matter is shown.

In a note on the distances of the cluster-type variables[1] it was suggested that the star-streaming discovered by Kapteyn, the phenomenon of "two star-streams," may be a consequence of the characteristic distribution of high-velocity vectors in our neighborhood of space. This gets special support by the flagrant fact that the line combining the true vertices of the two star-streams is almost exactly at right angles to the direction of the asymmetrical drift of the high-velocity stars. The recent papers by Strömberg[2] bearing on the phenomena associated with very high velocities may make it worth while to consider the matter more in detail.

It was assumed in the paper mentioned that part of the spreading of the high-velocity vectors in the galactic plane at right angles to the asymmetrical drift is due to encounters of the stars in question with the large clouds of stars and nebulosity constituting our "local system," which we may simply identify with the "Kapteyn universe." The ordinary star-streaming should be due to stars of smaller velocity falling in toward the local system, subject to the same gravitational forces and therefore suffering still greater deviations from their original paths, to such an extent that they may, at least for a long time, be counted as members of the local system.

A rough representation of the distribution of projections of stellar velocities on the galactic plane (including the high velocities) may be given by the formula

$$N = Ae^{-k(u^2+v^2)}dudv\,, \tag{1}$$

with the restriction

$$v < -\frac{u^2}{2p}\,. \tag{1a}$$

[1] *Astrophysical Journal*, **59**, 37, 1924.

[2] Mt. Wilson Communications, No. 84; *National Academy Proceedings*, **9**, 312, 1923. Mt. Wilson Contributions, No. 275; *Astrophysical Journal*, **59**, 228, 1924.

A, h, and p are constants; u, v, are the components of the velocities; N, the number of velocity-vectors within the element $dudv$. Here the axis of v is directed opposite to the direction of the asymmetrical drift of high velocities. The velocities of a certain size are thus assumed to be distributed uniformly within the parabola $u^2 = -2pv$.[1] The dispersion of the w-component in the directions of the galactic poles is known to be smaller than the dispersion in u. This circumstance may be due to the scattering influence of the local system in the way developed below; outside of the local system and similar aggregations of matter we may assume the dispersions in u and w to be equal, and the conditions for a steady state of motion, including motion of rotation around an axis of symmetry[2] of the big stellar system, to be satisfied. The axis of u should then point toward this center, which seems to be at least approximately the case. The u-direction lies, in fact, only about 20° toward increasing galactic longitude from the direction toward the center of the system of globular clusters according to Shapley.

The reason why the scattering power of the local system should work more strongly in the u- than in the w-component of the velocity is simply the concentration of the stars toward the galactic plane. A much larger number of stars will be scattered sideways parallel to the galactic plane than at right angles to it.

Allowing for this effect of spreading by the local system, we may assume tentatively that at a point far away from local irregularities and density-gradients the inequality (1a) should be replaced by

$$v < -|u| ; \qquad (1b)$$

and we assume that, in harmony with the conditions for a steady state of motion of the big stellar system, the dispersions in u and w are the same at such a point.

The permanent members of the local system, which we may suppose form a "nucleus" of the system with small internal motions, may be considered represented by a single unit at the velocity $u = 0$, $v = 0$. The expressions (1) and (1b) thus represent only those

[1] This accounts approximately for the relation between dispersion and asymmetrical drift found by Strömberg.

[2] Cf. Jeans, *Monthly Notices of the Royal Astronomical Society*, **76**, 81, 1915.

stars which are free to move outside of the local system, and this is the reason for the sharp point at $u=0$, $v=0$, following from the restrictive assumption (1*b*). The form chosen for this expression is, in other respects, not essential, as long as we do not know more about the dynamics of the big system.

The expressions (1) and (1*b*) may be interpreted physically on a still wider basis in the following way. The velocity $u=0$, $v=0$, represents a purely orbital motion of a system around the center of the big system, with internal motions. We may assume that the purely Milky Way clouds, or more strictly their nuclei, which evidently form a very flattened system, are represented by this velocity. Our local system has then to be identified simply as a Milky Way cloud. With decreasing orbital motion the internal dispersion of the velocities increases, and the stars can no longer belong permanently to the clouds, but move freely as members of the bigger system. There seems to be a continuous transition from the state of motion of the Milky Way clouds to that of the system of globular clusters. Judged from the results for the motion of the spiral nebulae, and from the flattened form of the last-mentioned system, this system must probably be supposed to have a general motion of rotation also.

The object is to show how the actual distribution of velocities can be derived from a distribution of velocities of the type represented by relations (1), (1*b*).

Let x, y, be co-ordinates in the galactic plane such that

$$u=\frac{dx}{dt}, \qquad v=\frac{dy}{dt},$$

with the origin at the center of the scattering mass M (Fig. 1). Let, further, P be a point on the negative side of the y-axis at the distance $\bar{y}$ from M. We assume that very far from M and P the distribution of velocities is of the form (1), (1*b*), without further stream motion, only with the inclusion of a potential term due to M in the exponential, thus

$$\left.\begin{aligned} &N=Ae^{-h(u^2+v^2-2\Omega)}du\,dv\,, \\ &v<-|u|\,. \end{aligned}\right\} \tag{2}$$

Consider a velocity-vector moving originally, very far from M, parallel to the y-axis with the velocity V', and with the abscissa x'. In order that the velocity shall pass through P, it is easily shown that we must have

$$a(e^2-1)=2\bar{y}\,,$$

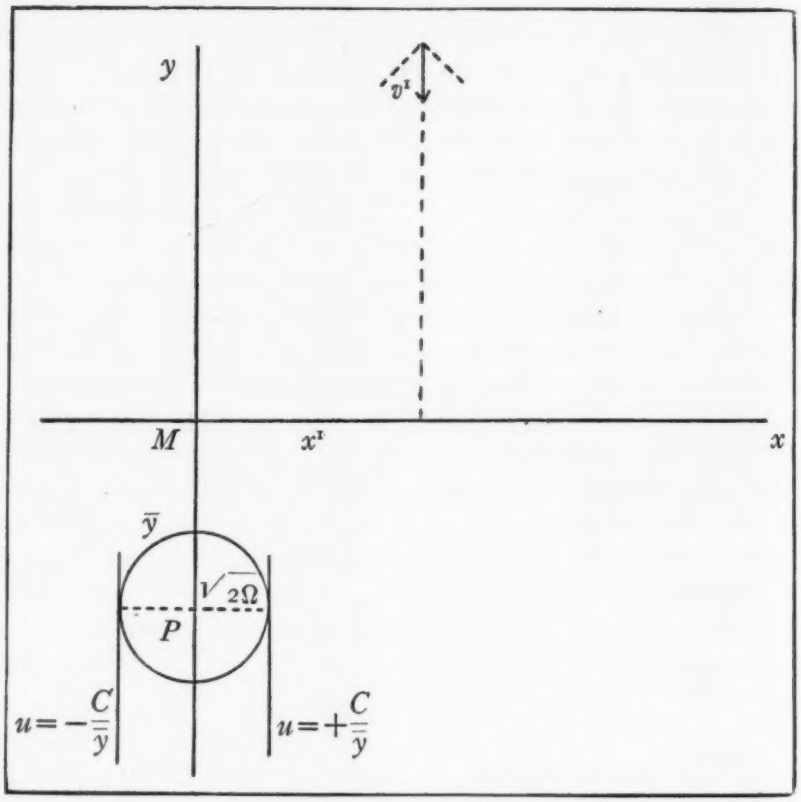


FIG. 1

where a is the semi-axis, e the eccentricity of the hyperbolic orbit around M. Now we have

$$xv-yu=-V'x'=\pm\sqrt{GMa(e^2-1)}\,,$$

where G is the constant of gravitation, thus

$$xv-yu=\pm\sqrt{2GM\bar{y}}=C=const.\,, \tag{3}$$

independently of the eccentricity of the orbit. For velocities V' of other directions, with components u', v', but obeying the condition $v' < -|u'|$, the angular momentum necessary for passage through the point P will vary with the eccentricity of the orbit, but only to a comparatively slight extent. Another reason for non-compliance with the relation (3) will be found in disturbances of the star on its way by the gravitational action of other masses than M.

We want to know the distribution in u, v, of fairly small velocities in the region around P. The number of stars of given u, v, having an angular momentum without regard to sign *slightly smaller* than $\sqrt{2GM\bar{y}}$, may be assumed to be proportional to

$$e^{-n[C^2-(xv-yu)^2]}, \tag{4}$$

where n is a constant, and thus the distribution of velocities at P (because the exponential in [2] is an integral of the motion) will be

$$\left.\begin{aligned} &N = A_1 e^{-h(u^2+v^2-2\Omega)+n\bar{y}^2u^2} du dv, \\ &v' < -|u'|, \qquad u^2+v^2 \geq 2\Omega, \quad |\bar{y}u| \leq C. \end{aligned}\right\} \tag{5}$$

The distribution of velocities will thus be represented by the velocity-ellipse (or hyperbola, if $n\bar{y}^2 > h$)

$$(h-n\bar{y}^2)u^2+hv^2 = \text{const.}, \tag{6}$$

having its greatest elongation at right angles to the asymmetrical drift of the high velocities.

Velocities of a certain original direction excluded by the condition $v' < -|u'|$, having the constant angular momentum $\sqrt{2GM\bar{y}}$, can only pass close to P for a very limited range of the eccentricity of the orbit, and will pass in the direction of the positive y-axis, i.e., with $v > 0$. The restriction $v' < -|u'|$ may therefore be assumed to give at least the lower half of the velocity-ellipse (6), i.e., the half of the ellipse on one side of the major axis. Because n must be supposed to be of appreciable magnitude, the second restriction $u^2+v^2 \geq 2\Omega$ will practically have only two transverse streams in opposite directions along the major axis. The third condition $|\bar{y}u| \leq C$ will limit these stream-velocities to the velocity in the parabola with vertex at P.

If we consider velocities of angular momentum somewhat exceeding $\sqrt{2GM\bar{y}}$, the number of stars of given u, v, will be assumed proportional to

$$e^{-n[(xv-yu)^2-C^2]},$$

and the velocity-ellipse will be

$$(h+n\bar{y}^2)u^2+hv^2=\text{const.}, \tag{7}$$

with the restrictions

$$v'<-|u'|, \quad |\bar{y}u|>C,$$

having the major axis parallel to the y-axis. The condition $v'<-|u'|$ will exclude the upper part of the ellipse. The remaining part will show transverse symmetrical star-streaming parallel with the x-axis, with a tendency to an asymmetrical drift in the direction of the negative y-axis along the lines $u=\pm C/\bar{y}$.

We must, however, make a special remark here. We have assumed the mass M to be a nucleus of high density, so that the force is everywhere proportional to r^{-2}. This will not be the case if M is an aggregation of stars or very thin nebulosity. Then we must assume that for a star passing through the attracting mass the attracting force decreases with decreasing r. The character of the asymmetrical drift will be somewhat different for this reason, because the stars passing near the origin on their way through P can have much smaller velocities than in the present theory.

In order to get quantitative estimations of the transverse star-streaming, we have to consider the two streams represented by the motions in opposite directions in the parabola with vertex at P.

The velocity V at P of a star moving in the parabola in question will be given by

$$V^2=GM\frac{2}{\bar{y}}.$$

Imagine a mass of ten million (10^7) solar masses in a sphere with radius 300 parsecs, which will give about one star of the mass of the sun in 10 cubic parsecs, a density which may be considered quite normal in an accumulation of stars. The velocity V at the boundary of the cluster will be 17 km per sec. The star-streaming at the boundary will be double this amount, thus, 34 km per sec.

If fairly isolated masses of the dimensions mentioned exist in the local system, there may be a star-streaming of the kind considered at several points of the local system, and this must in the course of time affect the velocity-distribution in the local system as a whole, as there will be no similar streaming in other directions.

In any event, if our conception of the local system has to be widened, in respect to the character of motion, to include the Milky Way clouds as a whole, it seems very possible that we may have to include in our consideration discrete accumulations of matter sufficient to produce a general transverse star-streaming of the observed magnitude.

The theory of Jeans,[1] attempting to interpret star-streaming as due to circular motion in both directions around the center of the local system, need not, of course, stand in absolute contradiction with the present considerations. From the point of view of that theory, the star-streaming considered here may be the ultimate cause of the rotations in opposite direction around the center of the local system. But if the observed star-streaming is supposed to be due entirely to such circular rotations, the coincidence of the line of the vertices with the normal to the direction of the asymmetrical drift of high velocities must be considered as a mere chance, due to the circumstance that the direction toward the center of the local system happens to coincide with the line of asymmetrical drift.

OBSERVATORIUM, UPSALA
December 1924

[1] *Op. cit.*, **82**, 122, 1922.

NOTE ON A STELLAR LINE AT 4470.046 A[1]

By OTTO STRUVE

ABSTRACT

Stellar spectra of types O9–B3 show a faint absorption line on the violet side of the helium line 4472. The wave-length of this line was found to be 4470.046 A on Rowland's scale. In stars which have broad and diffuse lines, the faint line at 4470 is blended with the helium line and tends to vitiate velocities determined from that line. The suspicion that this line might be due to ionized lithium could not be established at present.

While examining spectrograms obtained at the Yerkes Observatory for the determination of radial velocities of stars of spectral types B and O, I have noted that several stars had a faint absorption line on the violet side of the strong helium doublet 4471.646. Upon investigation I found that this line appears in practically all stars of spectral types B2 and B3, provided that the helium line is sufficiently narrow not to blend with its faint neighbor. The new line could not be detected in stars of spectral type earlier than O9. A trace of it is suspected in the spectrum of 10 Lacertae, which has very narrow and well-defined lines and which belongs to spectral type O9. The line is occasionally visible in spectra classified as B1, and it is fairly strong in type B2. It reaches maximum intensity in type B3 and is not found in any later spectral subdivisions. In some stars which have broad and ill-defined lines the faint companion is not visible separately from the helium line. However, its presence is indicated by the abnormally low velocities determined from the helium line with which it is combined in such cases. The existence of such a blend in spectra of early B-type stars is especially dangerous in the determination of radial velocities, since in a great many of these stars helium 4472 is the most conspicuous line and occasionally the only line suitable for measurement. This refers especially to stars with broad lines, since in most of these stars the fainter lines are too weak and hazy for accurate measurement.

The wave-length of this unknown line was determined from measurements of thirteen spectrograms taken with a dispersion of three prisms. Only spectra were used on which the separation of the

[1] The wave-lengths used in this paper are expressed on Rowland's scale.

two lines was complete or nearly so. The average of all measurements is 4470.046 A, with a probable error of ±0.035 A. The probable error of one plate is ±0.126 A. The table contains the results for each plate separately.

The new line could not be identified with any of the known lines of such elements as would be likely to occur in stars of types O9–B3. It cannot be the titanium line 4468.663 or the iron line 4469.545. No such line is listed among the stellar lines observed by Miss

TABLE I

Plate	Star	Spectral Type	Wave-Length
B 403	85 ι Herculis	B3	4470.006
B 1076	85 ι Herculis	B3	4470.002
B 1097	85 ι Herculis	B3	4470.099
B 1104	85 ι Herculis	B3	4470.302
B 1111	85 ι Herculis	B3	4470.052
A 281	17 ζ Cassiopeiae	B2	4469.902
A 355	17 ζ Cassiopeiae	B2	4470.140
B 466	3 π^4 Orionis	B3	4469.778
B 468	3 π^4 Orionis	B3	4470.137
B 383	82 δ Ceti	B2	4470.013
B 388	82 δ Ceti	B2	4469.985
B 404	82 δ Ceti	B2	4470.080
B 432	82 δ Ceti	B2	4470.094
Mean	.....	.....	4470.046±0.035

Cannon in "The Spectra of Bright Stars,"[1] nor is it given in the list of stellar lines used for the determination of radial velocities at Victoria.[2] It does not occur in F. E. Baxandall's recent "List of Lines of Unknown Origin in Various Celestial Spectra."[3] The line may be identical with a bright line observed at λ 4469 in the spectrum of γ Argus by W. W. Campbell.[4] Dr. Sebastian Albrecht very kindly advises me that he has in his old table for B-type stars a line with the wave-length 4469.83. This line is undoubtedly the same as the line observed by me.

It does not seem impossible that this line may belong to the ionized atom of one of the lighter elements. At first it was thought

[1] *Annals of the Harvard College Observatory*, **28**.

[2] *Publications of the Dominion Astrophysical Observatory*, **2**, 7–10, 1921; **2**, 301, 1924.

[3] *Monthly Notices of the Royal Astronomical Society*, **83**, 166, 1922.

[4] *Astronomy and Astrophysics*, **12**, 555, 1893.

that it may be due to ionized lithium. Since ionized lithium has the same number of electrons as neutral helium one would expect that the spectra of these two elements would resemble one another. At the same time it seemed possible that ionized lithium might have some such series of spectral lines which would be analogous to the "Pickering" or "ζ Puppis" series of ionized helium. This series, as is well known, contains lines which nearly coincide with the Balmer lines of hydrogen, being displaced by about 2 A to the violet from the hydrogen lines. Unfortunately, our knowledge of ionized lithium is not sufficient to settle this point. Recent studies of this spectrum by Mohler,[1] by Schüler,[2] and by Sven Werner[3] indicate an unusually high ionization potential for lithium. The lines found by Schüler and by Werner do not indicate any such series as might coincide or nearly coincide with the $(1\pi - m\delta)$ series of helium, of which the line 4472 is a member. The difficulty with which the spectrum of ionized lithium is obtained in the laboratory and the unexpectedly high value of the ionization potential seem to indicate that lithium behaves differently from other elements. In any case, the question of the identification of the line at 4470 must be left open for the present.

For the determination of radial velocities it is important to know the relative intensities of the faint neighbor to the helium line in stars where the two lines are blended. To determine this ratio approximately, I utilized Lee's measures of the spectroscopic binary 8 π^5 Orionis.[4]

My examination of Lee's measures of fifty-six spectrograms obtained with the dispersion of one prism, on which the helium line 4472 had been used, showed that the velocity determined from this line is systematically smaller than from other lines. The average difference is -3.6 km/sec., which corresponds to a difference of 0.056 A in the adopted value of the wave-length. Since the difference between the wave-lengths of the two lines is about 1.600 A, we find that the weights with which the two lines are blended must be

[1] *Physical Review*, **23**, 108, 1924.

[2] *Die Naturwissenschaften*, **12**, 579, 1924.

[3] *Nature*, **115**, 191, 1925.

[4] *Astrophysical Journal*, **38**, 180, 1913.

about one to thirty. In other words, the faint line is about thirty times or 3.7 stellar magnitudes fainter than the helium line. There is no doubt that this result is approximately correct. Direct estimates on spectrograms where both lines are visible gave a ratio averaging about twenty. In some stars, however, the fainter line is relatively much stronger, although it probably never reaches one-half the intensity of the helium line.

YERKES OBSERVATORY
April 20, 1925

RADIATION MEASUREMENTS OF THE SOLAR CORONA JANUARY 24, 1925[1]

By EDISON PETTIT and SETH B. NICHOLSON

ABSTRACT

Intensity and spectral distribution of the coronal radiation.—A vacuum thermocouple with a rock-salt window was placed at the focus of a 50.5-cm mirror of 101-cm focal length. Measurements were made differentially between two points in the corona 4′.6 from the east and west limbs of the moon and the moon itself. The *mean intensity of the coronal radiation* at these points was found to be 5.40×10^{-7} of sunlight. By means of a water-cell and thin glass plate it was found (1) that the corona radiates slightly more energy on the violet side of 1.3 μ than the sun does, and (2) that the radiation of wave-length greater than 5.5 μ is inappreciable.

Photometry of the corona.—The corona was photographed on plates provided with standard photometric squares. Two exposures were made upon Seed 30 plates without filter, and one upon an Ilford "Special Rapid Panchromatic" plate with red filter. These plates were rotated beneath the slit of the registering microphotometer, which, beginning at the limb, recorded the transmission curves of contiguous zones about the moon. These curves gave the mean intensity for each zone in arbitrary units. A similar record of the zone through the points occupied by the thermocouple junctions of the radiation apparatus, combined with the radiometric measures at these points, furnished a calibration by means of which the mean intensity in each zone could be expressed in absolute units. The summation of the zone intensities from the Seed 30 plates gave for the intensity of the whole corona 10.1×10^{-7} times sunlight, while 10.7×10^{-7} sunlight was found from an Ilford plate with red filter. The introduction of the solar constant gave for the coronal radiation 19.3×10^{-7} cal. cm^{-2} min.$^{-1}$. The ratio of the observed coronal light to full-moon light was 0.47.

Distribution of energy in the corona.—The corrections for scattering of the coronal light and halation in the plate were found from transmission curves taken radially across the moon and the edges of the plate. These corrections were applied to the zone intensities. From the corrected intensities, it was found: (1) that the intensity in the polar region is less than half that in the equatorial region, (2) the intensity of a point in the corona as derived from Seed 30 plates varies inversely with the sixth power of its distance from the center of the sun, (3) the ratio of blue light to red light varies directly with the distance from the center of the sun, (4) the correcting factor for overlapping moon varies with the fourth power of the ratio of the apparent radius of the moon to the apparent radius of the sun.

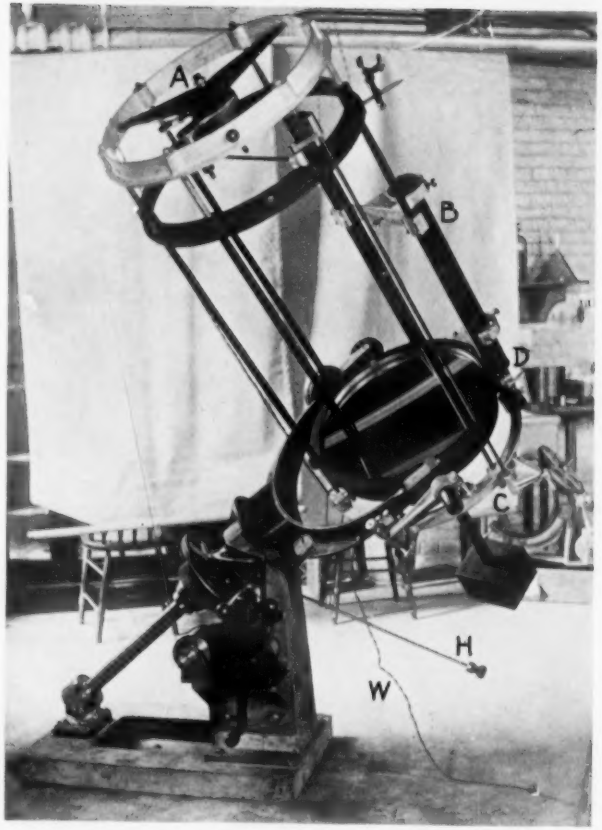
Radiation from the whole corona.—When corrected for overlapping moon the radiation from the whole corona is 21.4×10^{-7} cal. cm^{-2} min.$^{-1}$, or 0.52 full-moon light. Comparison with photo-electric cell measures gives some evidence that the intensity of the coronal light varies with the solar constant, but with a greater amplitude.

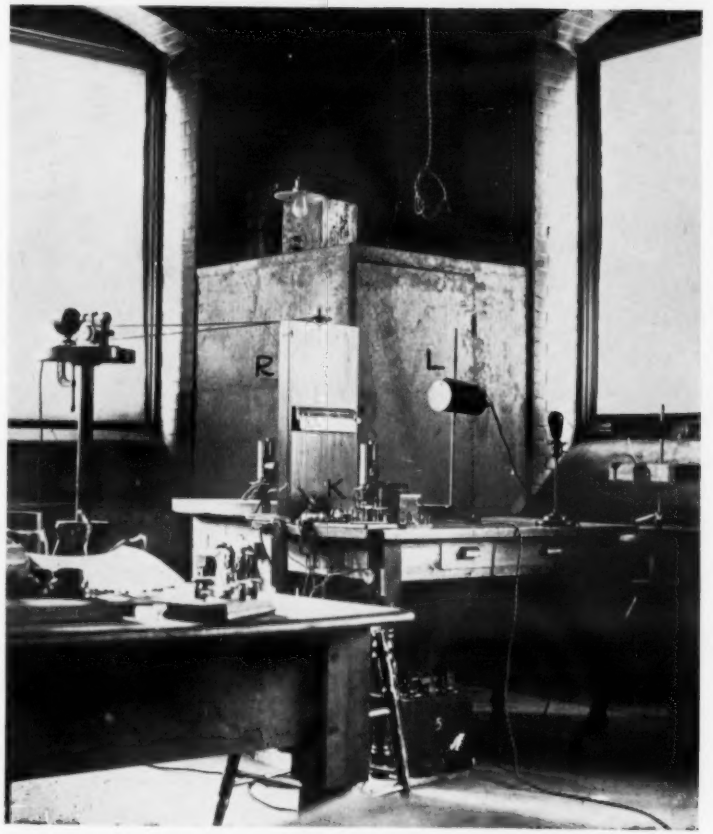
Observation of the corona without an eclipse.—The intensity of scattered light about the image of the sun in optical instruments is at least one hundred times greater than the maximum allowable for detecting the corona without an eclipse by any radiation method.

The radiation from the corona was measured with the vacuum thermocouple at Middletown, Connecticut, during the eclipse of January 24, 1925. Briefly, the plan was (1) to determine the amount and spectral distribution of the radiation from a small area of the

[1] *Contributions from the Mount Wilson Observatory*, No. 299.

PLATE IV





REFLECTING TELESCOPE AND THERMOCOUPLE AS USED FOR OBSERVATIONS OF CORONAL RADIATION

The galvanometer and recording apparatus shown on the right were mounted in an adjoining room

corona with a suitable thermocouple attached to a reflecting telescope and (2) to determine the distribution of energy in the corona by photographic photometry. The results from (1), combined with (2), would then give the total amount of radiation emitted by the corona, expressed in absolute units.

Measurements of the coronal radiation have previously been made by Abbot, during the eclipses of May 28, 1900,[1] at Wadesboro, North Carolina, and of January 8, 1908,[2] at Flint Island. Abbot used a bolometer with a glass window, attached to a telescope of 50.5-cm aperture and 100-cm focal length. Only one strip of the bolometer was exposed to the radiation, the deflections being produced by means of a shutter. A screen consisting of an asphaltum-coated glass plate was used to filter out the visual light, thus leaving only the infra-red radiation. Abbot found that the spectral distribution of radiation in the regions measured was nearly the same as, though slightly redder than, that of light from the center of the sun's image, and that the brightness of the inner corona equaled that of lunar radiation transmitted by glass.

THE APPARATUS

The telescope and auxiliary equipment employed at the eclipse of January 24, 1925, are illustrated in Plate IV. The whole apparatus was set up in the basement of the Scott Physical Laboratory of Wesleyan University, through the kind invitation of W. G. Cady, in charge of the laboratory, who placed at our disposal the many conveniences and the equipment of the institution. The telescope carried the 50.5-cm mirror used by Abbot at Flint Island in 1908, which was kindly placed at our disposal by him. The figure of the mirror in the meantime has been slightly altered, however, its focal length now being 101 cm, so that the image of the moon at the time of the eclipse was 9.79 mm in diameter.

The thermocouple and transmission cells were mounted at *A* (Plate IV), directly in the principal focus of the mirror. The thermocouple was provided with a rock-salt window to permit the measurement of all radiations received by the mirror of the telescope. It

[1] *Astrophysical Journal*, **12**, 69, 1900.

[2] *Smithsonian Miscellaneous Collections*, **52**, Part I, 31, 1908.

had two junctions 0.76 mm square, separated 5 mm, a distance about equal to the radius of the moon's image formed by the mirror at the time of the eclipse.

The reticule in the guiding telescope *B* contained three threads, one parallel to the diurnal motion of the telescope and two others, one fixed and one movable, intersecting the first thread at right angles, and so spaced that their angular separation in the field of the finder was the same as that of the junctions of the thermocouple in the field of the reflector. The adjustment was such that when the telescope was shifted in right ascension so that a star seen in the guiding telescope moved from one intersection to the other, the image formed by the reflector moved from one thermocouple junction to the other. During the eclipse one limb of the moon was set on a speck of dust near the movable wire, and at the signal for shift the other limb was set at an equal distance from the fixed wire. This caused the junctions to be set alternately on the corona at two points 4′.6 from the east and west points of the limb of the moon, while the opposing junction was on the moon 12′.4 inside the limb.

Two transmission cells were provided to study the spectral distribution of the energy in the corona. One of these was a water-cell 1 cm thick, the other a microscope cover-glass 0.165 mm thick. Their transmission curves have already been given.[1] These cells could be interposed into the beam from the 50.5-cm mirror by turning the lever *C*. The insertion of the water-cell increased the effective focal length of the mirror about 2.5 mm. This was compensated by giving the lever *D* a quarter-turn, which moved the thermocouple and cells away from the mirror just the proper amount.

The telescope was set close to a window which was provided with a shutter, hinged at the lower casing. The purpose of the shutter was to prevent sunlight from striking the mirror, as the intense image would have melted the thermocouple instantly and set fire to its insulation. At the signal of totality, the shutter was thrown open, and closed again a few seconds before the end of totality. While protecting the mirror of the telescope, the shutter did not cover the guiding telescope, which was set upon the moon before the eclipse

[1] *Mt. Wilson Contr.*, No. 246; *Astrophysical Journal*, **56**, 312, 1922; *Publications of the Astronomical Society of the Pacific*, **35**, 195, 1923; *Popular Astronomy*, **32**, 602, 1924.

began. The tube of the telescope was covered with heavy black paper, which extended about 50 cm beyond the end of the skeleton frame in order to protect the thermocouple, as far as possible, from drafts and stray radiation. A twisted lamp-cord *W* conveyed the current produced by the thermocouple at *A* to the galvanometers set up in an adjacent room.

Two Leeds and Northrup high-sensitivity D'Arsonval galvanometers were provided, having periods of five and one seconds, respectively. These were arranged on a pier so that, with the aid of fixed mirrors, an image of the filament of a 100-watt lamp *L* was cast by each upon the double slit[1] of the photographic registering device *R* at a scale distance of 7.5 m. By means of a switch, either galvanometer could be put into the thermocouple circuit in series with a resistance box.

Observations of the radiation from the moon indicated that the one-second galvanometer without additional resistance in the circuit would probably be sufficiently sensitive, and this arrangement was used during the eclipse. Had the sensitivity been too great, it could have been decreased by pulling plugs out of the resistance box, or had it been too small, the five-second galvanometer, the sensitivity of which was six times greater, could have been put into the circuit with little loss of time.

Observations of the radiation from a lamp showed that with the thermocouple used, the one-second galvanometer came to full deflection in seven seconds. A clock-driven electric contact *K* was then arranged to give signals at the telescope at intervals of seven seconds, at each of which the observer shifted the telescope by means of the right ascension slow motion handle *H*, so that the corona and the center of the moon interchanged places on the junctions of the thermocouple. A marker placed on the screw of the registering device indicated when the cells should be thrown into the beam from the telescope, and this was signaled by a buzzer.

The photometric device consisted of a 6-in. Ross doublet of 15-ft. focal length, fed by a coelostat with a 6-in. pyrex mirror.[2] Three plates were exposed, two Seed 30 without filter and an Ilford "Spe-

[1] *Journal of the Optical Society of America*, **10**, 267, 1925.

[2] *Mt. Wilson Contr.*, No. 266; *Astrophysical Journal*, **58**, 208, 1923.

cial Rapid Panchromatic" with Eastman "F" filter, which transmits only wave-lengths longer than 6100 A. Photometric squares were exposed along the end of each plate by the usual method of varying the distance of the plate from an electric light operated from a storage battery. The energy ratios for these squares computed from the inverse square law are represented by the numbers 1.000, 0.444, 0.250, 0.111, 0.062, 0.028, and 0.020. During the eclipse, exposures of two seconds and fifteen seconds, respectively, were given to the two Seed 30 plates, and an exposure of seventy-three seconds to the Ilford plate with red filter.

ECLIPSE CONDITIONS

The mild weather prevailing during the two preceding weeks turned suddenly cold the day before the eclipse, the thermometer indicating a temperature of about −8° F., a condition which continued until after the eclipse. The water-cell froze and broke, but was repaired and refilled with saturated salt water. A series of observations on the transmission of sunlight by the cell filled first with salt water and then with distilled water revealed no measurable difference. The coelostat operating the Ross lens ran somewhat slowly, but this did not affect the short exposures, although its effect was quite noticeable on the Ilford plate. The driving clock of the 50.5-cm reflector ran very satisfactorily.

On the morning of the eclipse, the sky clouded suddenly about 6:00 A.M. and remained so until nearly 8:00 A.M., when the clouds began to break away. By 9:00 A.M. the sky was clear, save for a bank of haze in the east, and during the eclipse (9:12 A.M.) the sky was quite clear in the neighborhood of the sun.

Although excellent definition was not necessary, the windows of the laboratory-room where the telescope and coelostat were located were opened about forty minutes before totality, so that the room might come to outside temperature.

DISTRIBUTION OF ENERGY IN THE CORONAL RADIATION

During totality, five deflections were obtained for the free radiation, that is, without transmission cells, and four each for the radiation transmitted by the salt-water cell and microscope cover-glass. One deflection obtained with each of the cells was rejected, these

being obviously defective, as shown by the form of the curve on the plate. The deflections were measured on a suitable comparator[1] and gave the following results:

	Millimeters	
Free	65.4	(1)
Water-cell	47.1	
Cover-glass	61.4	

On account of the shadow cast by a part of the water-cell mechanism, the deflections for the free radiation from the corona have been multiplied by a small factor which increased the observed value from 65.2 to 65.4 mm. These are the only deflections requiring this correction.

In order to compare the coronal light with integrated sunlight, a small auxiliary mirror of 47.7-mm diameter and 40.5-mm focal length was placed centrally over the 50.5-cm mirror of the telescope, the latter being covered. Under these circumstances, the sunlight intercepted by the small mirror was spread over a circle 115 cm in diameter at the thermocouple. The distribution of the radiation over the segment of the spherical surface illuminated by this mirror, its focus being at the center and the thermocouple at the surface of the sphere, was investigated and found to be essentially uniform, although this is not always true for small spherical mirrors of short focal length. The distance from the thermocouple to the focus of the mirror being 88.5 cm, it is easily shown that the reduction factor of the mirror is 22.07×10^{-4} times direct sunlight.

The measures of integrated sunlight were made when the sun had nearly the same altitude, 17°40′, that it had during the eclipse. The deflections were obtained by placing a diaphragm over the thermocouple which exposed one junction only and then rotating the mirror between fixed stops about an axis perpendicular to its optical axis. The logarithms of the deflections were plotted against air-mass, and the value for air-mass 3.29 (that for the sun at eclipse time) was read from the plot. The deflections thus obtained were as follows:

	Millimeters	
Free	57.2	(2)
Water-cell	40.8	
Cover-glass	56.2	

[1] *Journal of the Optical Society of America*, 10, 267, 1925.

Since double deflections were observed in the case of the corona, these values for integrated sunlight must be multiplied by 2 in computing the amount of energy radiated by the corona.

The moon was observed on January 21 at 6:15 and 6:30 A.M., the phase-angle being then 136°.3. It was not possible to observe nearer full moon on account of the limits in hour-angle set by the window in the room where the telescope was placed. The deflections were made by setting the junctions each in turn upon the apparent center of the crescent. The logarithms of the deflections were plotted against air-mass, and the values corresponding to the sun's air-mass at eclipse time were obtained from these plots. The resulting deflections are:

	Millimeters
Free	183.5
Water-cell	21.1
Cover-glass	31.7

(3)

The results (1), (2), and (3) give the transmissions shown in Table I. This table shows that while the spectral distribution of

TABLE I

PERCENTAGE DISTRIBUTION OF ENERGY

	0.3 μ–1.3 μ	1.3 μ–5.5 μ	8 μ–14 μ
Corona	77.6	22.4	0.0
Sun	71.4	28.6	0.0
Moon (crescent)	12.5	6.6	80.9

coronal radiation is very much like that of sunlight, the corona emits a little more radiation on the violet side of 1.3 μ than does the sun. The difference, however, is relatively small and will require data from future eclipses to determine its value accurately.

Abbot,[1] at Flint Island, observed two points on either side of the sun, situated 4′ from the limb, a distance nearly the same as that of the points observed by us. One of these showed more radiation to the red of 1 μ and the other more to the violet of 1 μ than the sun. Whether these results, as compared with those obtained by us, indicate real differences in the corona or instrumental difficulties it is naturally impossible to decide.

[1] *Smithsonian Miscellaneous Collections*, **52**, Part I, 43, 1908.

From inspection of Table I it is patent, however, that there is no long-wave radiation beyond 5.5 μ. In future radiation measurements on the corona, glass or quartz windows can therefore be used on the measuring apparatus.

INTENSITY OF THE CORONAL RADIATION COMPARED WITH SUNLIGHT

We may compare the intensity of the coronal radiation or "surface brightness" of the corona at the points where the thermocouple junctions were placed with the intensity of direct sunlight by combining the data given under (1) and (2).

If, in making the observations on direct sunlight, the 50.5-cm mirror had been used with a diaphragm over it, having an aperture equal to the diameter of the image of the sun, and if the radiation were distributed uniformly over this image, the deflections observed would have been the same as those obtained on direct sunlight. The effect, then, of using the 50.5-cm mirror is to increase the deflections in the ratio of the exposed area of this mirror (1706 cm^2) to the area of the image of the sun (0.7156 cm^2). The ratio of the intensity of direct sunlight to the intensity of the image formed by the mirror is therefore 41.95×10^{-5}. Since the direct sunlight was weakened by spreading it over a large area by means of the small auxiliary mirror, this value must be multiplied by 22.07×10^{-4}, as has already been pointed out. This gives a total reduction factor of 9.26×10^{-7} to be used in comparing the deflections obtained from sunlight with those obtained from the corona.

The values of the deflections themselves from (1) and (2) are 65.4 mm for the free radiation from the corona and 114.5 mm for the free radiation from the sun, the latter including the factor 2 necessary to reduce to double deflections. From these data, we find that the ratio of the intensity of the coronal radiation to direct sunlight is 5.29×10^{-7}.

A correction must be applied to this quantity to allow for the fact that tne cold receiver on the image of the moon received some energy from the corona scattered by our atmosphere and the telescope. The observed value is therefore too small, and from the investigation of the scattered light discussed later, it appears that the

foregoing ratio should be increased by 2 per cent. The corrected value is therefore 5.40×10^{-7}.

From his observations at Flint Island in 1908, Abbot obtained the value 4×10^{-7} for the ratio of the radiation from points in the corona 4′ from the moon's limb and in position angle 50° from the east and west points to that of sunlight. In making his comparisons, he used the 50.5-cm mirror with a small diaphragm so that the bolometer was set on an image of the sun. We determined the ratio of the intensity at the center of such an image to the mean intensity over it from drift curves made with a large image in the Pasadena Laboratory and found it to be 1.16. This must be applied as a factor to Abbot's value to make it comparable with that obtained by us. His result is therefore 4.6×10^{-7} for a point 4′ from the moon's limb, while our value is 5.40×10^{-7} for a point 4′.6 from the moon's limb. Abbot's observations were made at the time of sun-spot maximum so that the corona was more uniformly distributed about the sun, while we observed near the east and west limbs of the sun at the time of sun-spot minimum, which will account for our somewhat greater value.

PHOTOMETRY OF THE CORONA

Plates V, VI, and VII show the photographs of the corona made with the Ross lens. The first two are exposures of two seconds and fifteen seconds, respectively, on Seed 30 plates without filter, while Plate VII is an exposure of seventy-three seconds on an Ilford plate with red filter, the positive used for reproduction being shaded to bring out the detail of the inner corona. Plate VIII is from the same negative as Plate VII, but is reproduced without shading. The much greater contrast in Plates VII and VIII is striking.

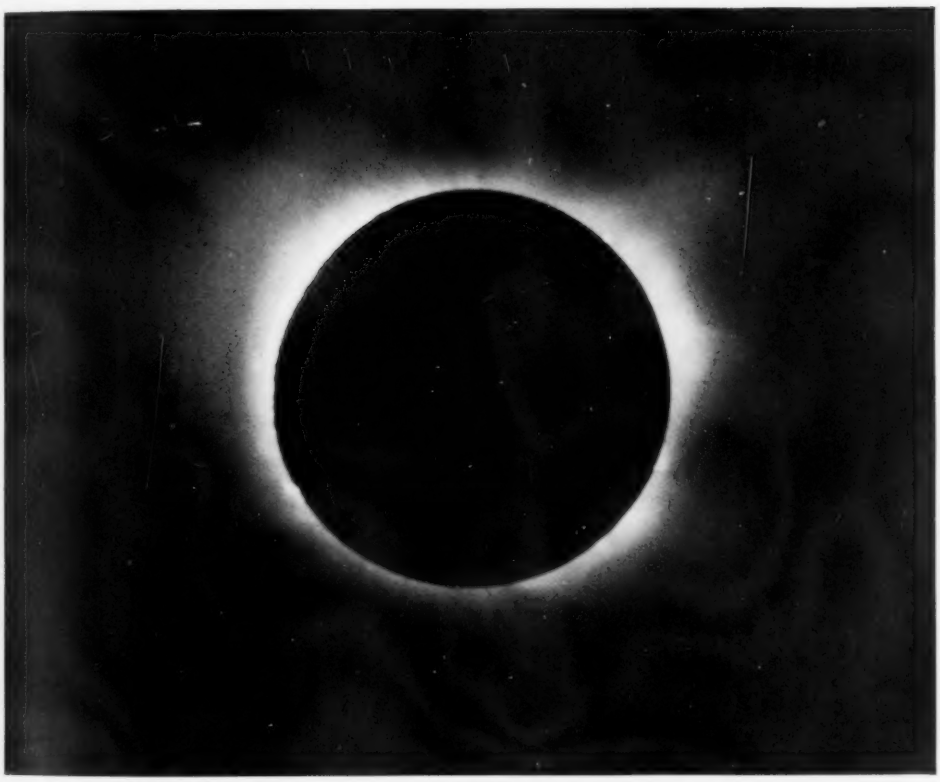
These plates were placed successively on the registering microphotometer,[1] and series of deflections were recorded for each photometric square and for the unexposed strip. From these data a table was made giving the intensities corresponding to any deflection of the galvanometer of the microphotometer in terms of the intensity of the light which formed the densest square.

[1] *Mt. Wilson Contr.*, No. 246; *Astrophysical Journal*, **56**, 314, 1922; *Journal of the Optical Society of America*, **7**, 187, 1923.

PLATE V

N

E



W

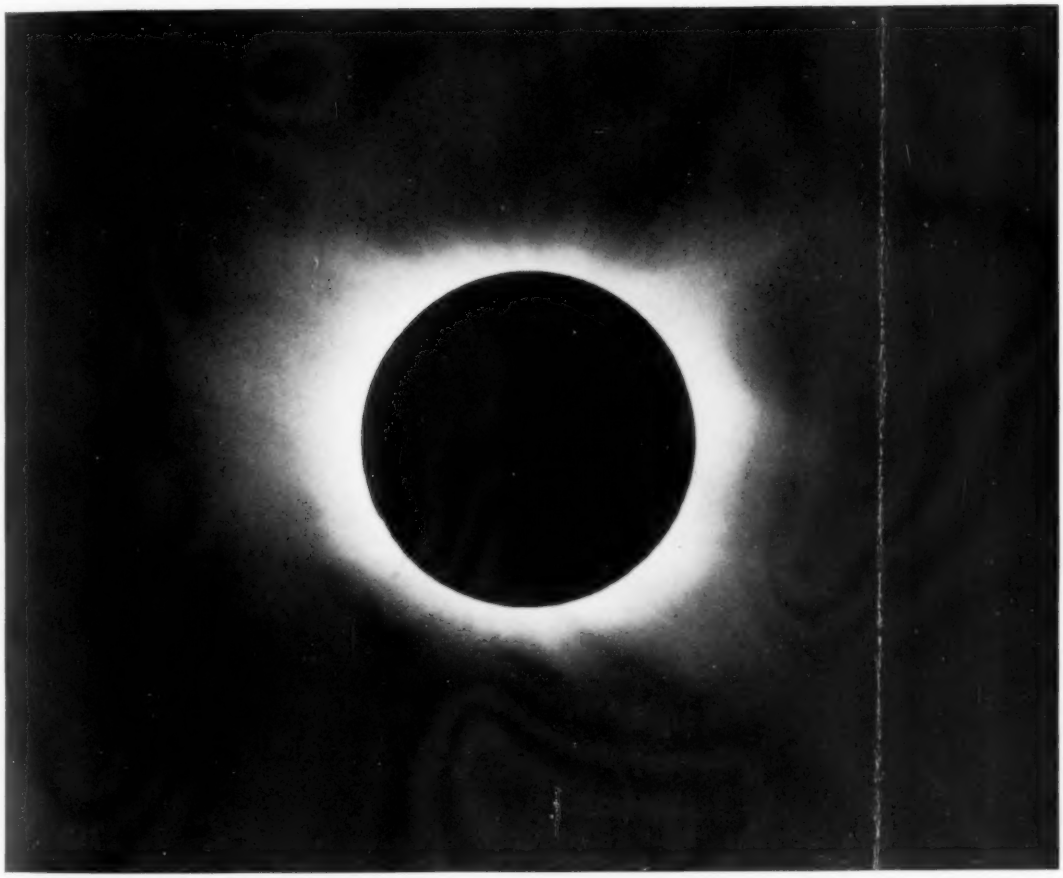
SOLAR CORONA OF JANUARY 24, 1925

Exposure of 2 seconds on a Seed 30 plate. Position of the sun's pole is 9° west of north

PLATE VI

N

E



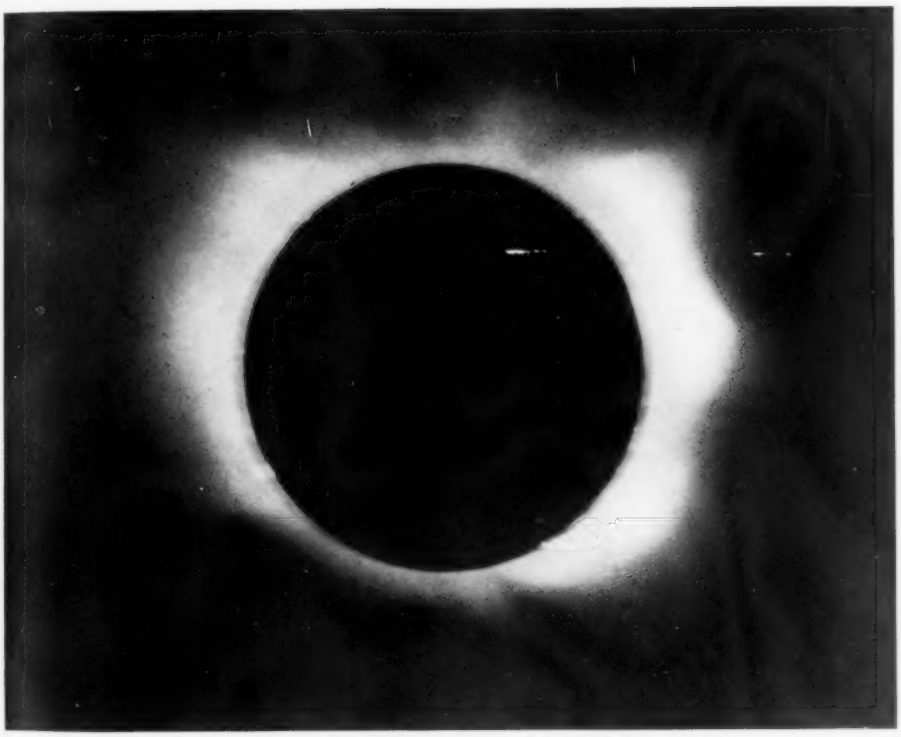
W

SOLAR CORONA OF JANUARY 24, 1925

Exposure of 15 seconds on a Seed 30 plate. Position of the sun's pole is 9° west of north

PLATE VII

N



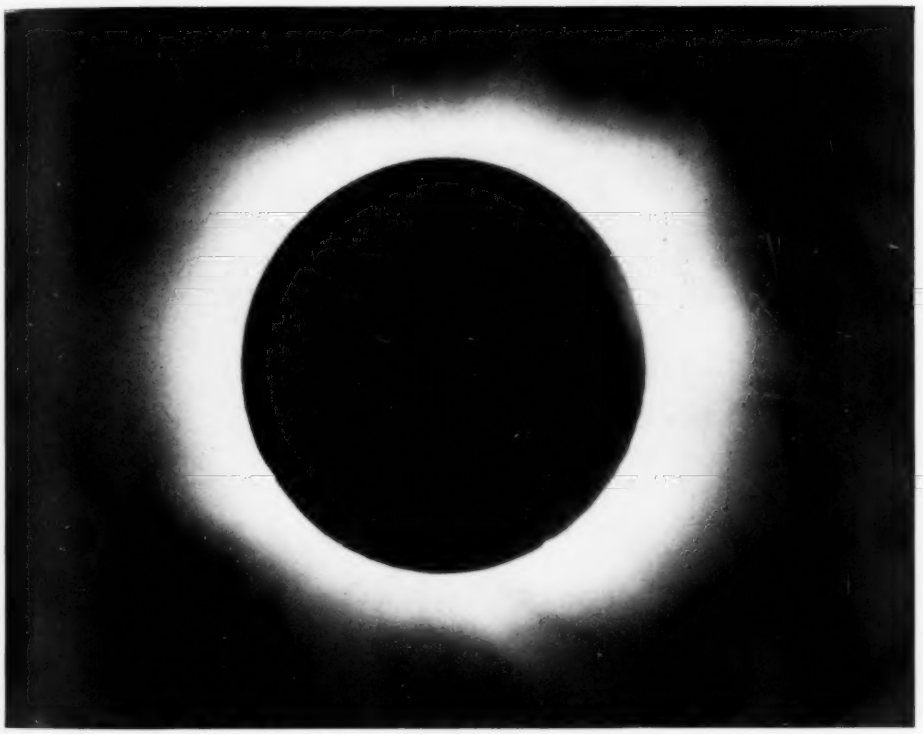
E W

SOLAR CORONA OF JANUARY 24, 1925

Exposure of 73 seconds on an Ilford Panchromatic plate used with a red filter. The positive used for reproduction has been shaded to bring out the detail of the inner corona. The position of the sun's pole is 9° west of north.

PLATE VIII

N



E W

SOLAR CORONA OF JANUARY 24, 1925

The positive used for reproduction was made from the same negative as Plate VII, but without shading.

The plates were then placed on a turntable which could be rotated beneath the photometer-microscope so that the slit, set perpendicularly to the moon's limb, described zones in the corona concentric with the image of the moon. The width of the zones was 0.16 solar radii, which was the length of a side of the square receiver of the thermocouple when projected upon the image of the sun in the field of the 50.5-cm mirror at the time of the eclipse.

Beginning at the limb, these zones were run contiguously. The upper part of Figure 1 shows a set of transmission curves obtained in this manner on the sixth, seventh, eighth, ninth, and tenth zones of the fifteen-second exposure. The scale of position-angles shown at the top of the figure was obtained with the aid of breaks made in each curve as the north point of the moon passed the photometer slit. The principal features of the corona can be traced in these curves by comparing the indicated position-angles (measured from the north toward the east) with Plates V, VI, and VII. A transmission curve was also run with the photometer slit set in zone 2.33, the same as that occupied by the thermocouple junction during the eclipse. This we shall call the "standard-plate curve."

To translate the transmission curves into curves of intensity, deflections (ordinates) were read with the measuring machine for each 2 mm of abscissa. The intensities were then derived from the table of intensity against galvanometer deflection. Three such curves are shown in the lower part of Figure 1, two for the third and one for the eighth zone. The ordinates of these intensity curves are on an arbitrary scale and have had the correction for general sky-illumination subtracted from them, the constant for which was obtained from the study of the distribution of energy in the corona. It is evident that the intensity of the coronal radiation in the equatorial regions is more than twice that in the polar regions.

To find the mean intensity in each zone in terms of the intensity of the light which formed the densest square, the deflection curves were laid on co-ordinate paper, from which were read the mean ordinates for intervals of 5 mm, the corresponding intensities being taken from the table as before. The mean of these intensities for each curve is the mean intensity in the corresponding zone.

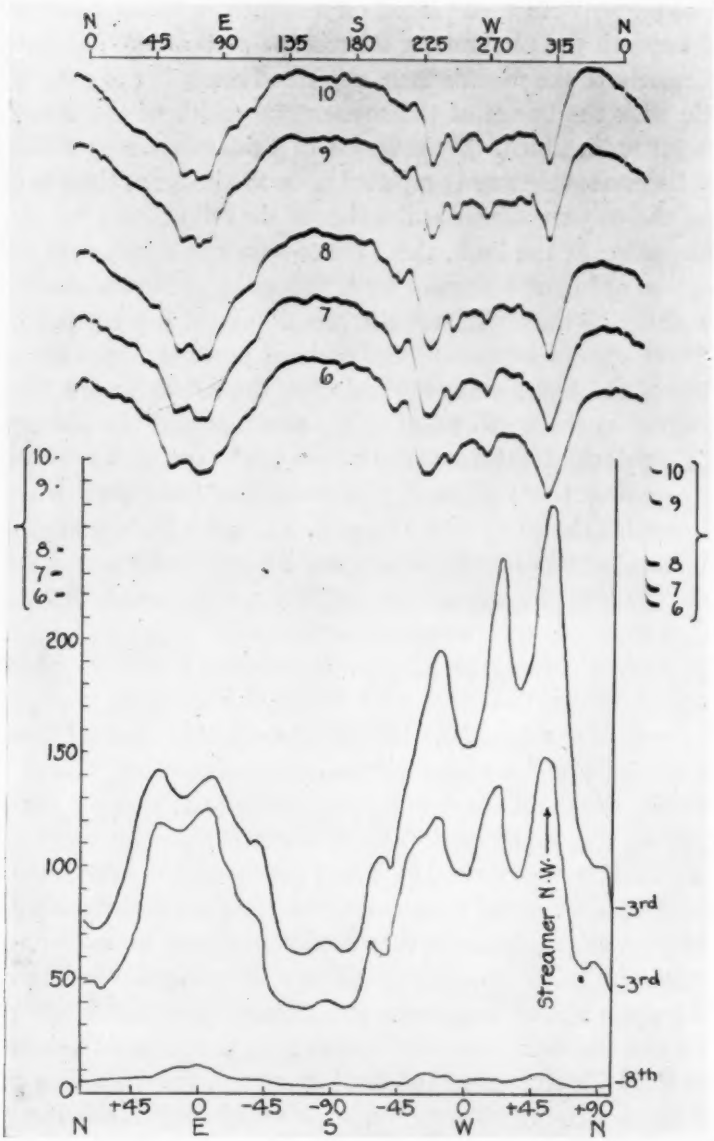


FIG. 1.—Transmission curves (above) for 15-second exposure on the corona (Plate VI), showing variations in density with position angle for zones 6 to 10. The corresponding intensity curves for the third (2-second and 15-second exposures) and eighth (15-second) zones are shown below.

BRIGHTNESS OF THE CORONA COMPARED WITH THE SUN AND THE FULL MOON

Before we can compare the brightness of the corona with that of the sun and moon, we must correct the measured intensities for general scattered light over the sky, most of which probably comes from sources outside the corona itself. This correction was taken to be equal to the mean intensity of the background of the plate measured at its four edges. This was found to be −0.040 on the two-second exposure, −0.020 on the fifteen-second exposure, and practically zero for the seventy-three-second plate taken through the red filter. That the correction for the two-second exposure is greater than that for the fifteen-second is probably due to the fact that it was taken immediately after second contact. The shadow had therefore just passed the observing station, and the sky was illuminated more strongly from without the shadow than during the fifteen-second exposure, which was taken later. In the case of the plate taken through the red filter, the scattering in those wavelengths affecting the plate would naturally be very small.

TABLE II

MEAN INTENSITY FOR DIFFERENT ZONES OF THE CORONA CORRECTED FOR GENERAL SKY-ILLUMINATION AND HALATION

ZONE NUMBER	MEAN RADIUS	AREA, *A*	INTENSITY, *I*, SEED 30			*IA*	INTENSITY, *I*, ILFORD	*IA*
			2-Sec.	15-Sec.	Mean			
1	1.11	0.355	0.595	0.546	0.570	0.202	0.815	0.289
2	1.27	.406	.228	.269	.248	.100	.277	.112
3	1.43	.458	.111	.137	.124	.057	.126	.058
4	1.59	.509	.063	.068	.066	.033	.065	.033
5	1.75	.560	.039	.041	.040	.022	.031	.017
6	1.91	.611	.027	.027	.027	.016	.016	.010
7	2.07	662	.019	.017	.018	.012	.008	.005
8	2.23	.714	.015	.012	.014	.010	.006	.004
9	2.39	.765	.010	.009	.010	.008	.004*	.003
10	2.55	.816	0.006	.007	.007	.006	.002*	.002
11	2.71	.867	.....	.005	.005	.004	.001*	.001
12	2.87	.918	.....	.004	.004	.004	.001*	.001
13	3.03	0.970	.....	0.003	0.003	0.003	0.001*	0.001
						$\Sigma IA = 0.477$		0.536

* Computed from the seventh-power law (see Table IV).

A second correction must be applied to each zone because of

halation. The values of this correction will be found in Table III, which was derived from a study of the law of scattering.

Applying these corrections to the observed intensities, we have the corrected intensities in the various zones for the three plates shown in Table II.

The second and third columns give the mean radius and area of each zone in terms of the radius and area of the sun; the fourth, fifth, and sixth columns give the mean intensities in the zones obtained

TABLE III

CORRECTIONS FOR SCATTERED CORONAL LIGHT AND HALATION

Zone Number	Seed 30		Ilford
	C	*H*	*H*
1	0.032	0.025	0.100
2	.027	.011	.015
3	.017	.004	0.000
4	.012	.002	.....
5	.009	0.000	.....
6	.006	.....	.....
7	.004	.....	.....
8	.004	.....	.....
9	.004	.....	.....
10	.004	.....	.....
11	.003	.....	.....
12	.003	.....	.....
13	0.003	.....	.....

from the two Seed 30 plates and the mean for the two plates, while the eighth column gives similar data for the Ilford plate with red filter.

If we let I be the mean intensity in a zone, I_e the average of the two intensities at the east and west points on the standard-plate curve (the intensities at the two points in the corona occupied by the thermocouple junctions), and A the area of the zone in terms of the area of the sun, the total energy of the corona, E, in terms of sunlight is given by

$$E=\frac{5.40\times 10^{-7}\,\Sigma IA}{I_e}\,. \qquad (4)$$

The values of IA found from the Seed 30 plates, and their sum, are given in the seventh column of Table II, while similar data for

the Ilford plate are in the ninth column. For the Seed 30 plates, I_ϵ was found to be 0.256, and for the Ilford plate, 0.271.

Substituting these values into equation (4), we find that the intensity of the coronal light in terms of the light from the sun is 10.1×10^{-7} for the Seed 30 plates, and 10.7×10^{-7} for the Ilford plate with red filter. Since these values are in good agreement, it appears that we are justified in applying the measurements of radiation with the thermocouple, which cover all wave-lengths emitted by the corona, to the photometric observations, which cover limited regions in the violet and red, respectively. Since, however, the Seed 30 plates cover a range of wave-length which is greater than that covered by the Ilford plates and is also nearer the region of maximum solar radiation, we shall adopt the value 10.1×10^{-7} in preference to the mean of the two results, as more nearly representing the energy measured by the thermocouple.

Since the radiation from the corona appears to have nearly the same spectral energy characteristics as sunlight, its absorption factors for the atmosphere will be nearly the same; hence we may apply the solar constant to the ratio of coronal light to sunlight to obtain the radiation of the corona outside the atmosphere. While no measurements of the solar constant are available for the first of the two days on which solar radiation was observed by us, its value has been inferred from results furnished by Dr. Abbot for a period of twelve days, including the eclipse day. From these data it seems very probable that the mean value of the solar constant for the two days was 1.91 cal. cm^{-2} $min.^{-1}$ Applying this to the value of E adopted above, we have for the radiation from the corona, the sun being at mean distance,

$$E = 19.3 \times 10^{-7} \text{ cal. cm}^{-2} \text{ min.}^{-1} \qquad (5)$$

According to Russell,[1] the visual light of the full moon is 21.5×10^{-7} times sunlight, both sun and moon being at mean distance. On account of the large number of observations used, which were more or less differential, this value should be free from the variability of solar radiation. Since the coronal radiation does not differ greatly from sunlight in spectral distribution, and since both corona and

[1] *Astrophysical Journal*, **43**, 125, 1916.

sun were observed at the same distance, the ratio of the coronal light to the light of the full moon at mean distance, for the visual region of the spectrum, is

$$\frac{\text{Corona}}{\text{Full moon}} = \frac{10.1 \times 10^{-7}}{21.5 \times 10^{-7}} = 0.47 . \qquad (6)$$

This agrees as well as can be expected with the provisional value 0.5 obtained visually by Professor Parkhurst[1] with an adaptation of the Hartmann microphotometer at this same eclipse.

At the eclipse of September 20, 1922, Briggs[2] determined the ratio of the brightness of the corona to the full moon, using two photo-electric cells. The values given by him are not reduced to mean distance, and since his comparisons were made at apogee, they are subject to a correcting factor of 1.11. It is also evident that the first two mean intensities given in the sixth column of Table III of his paper should be reduced to full phase, and further, that the mean of the three determinations would probably give a better standard than the last value alone. Using the data given by Russell[3] to correct to full phase, and applying the factors 0.981 and 0.967 to reduce them to the distance of the sun at eclipse time, we find from Briggs's observation that the values of the brightness of the moon at "no atmosphere" are 2.19, 2.13, and 2.18 candle-meters. If we adopt the mean of these, 2.17, the value for the moon at mean distance would be 2.41 candle-meters and the mean of Briggs's six determinations for the ratio of the corona to the full moon at that eclipse becomes 0.33.

Kunz and Stebbins,[4] observing with the photo-electric cell, obtained the value 0.50 at the eclipse of June 8, 1918.

At least a portion of the differences between these results can be accounted for by the overlapping of the moon on the inner corona. In order to examine this effect it will be necessary to determine the law of radial distribution of energy within the corona.

[1] *Publications of the Astronomical Society of the Pacific*, **37**, 85, 1925.

[2] *Astrophysical Journal*, **60**, 280, 1924.

[3] *Ibid.*, **43**, 125, 1916.

[4] *Ibid.*, **49**, 151, 1919.

DISTRIBUTION OF ENERGY IN THE CORONA

In studying the distribution of energy in the corona, it is necessary to correct the observed intensities for scattered light originating in the corona itself and also in the film of the plate in the form of halation. To determine these corrections, transmission curves were registered diametrically across the moon's image in position-angles 0° and 90°. Deflections were also registered for the transmission at the edge of the plate where the general sky-fog alone was effective.

The amount of scattered light on a given region of the image is evidently not constant, as Bergstrand[1] and others have assumed, but is greater over the brighter parts than over the fainter regions. To find the law of distribution of the light scattered from the corona, it was first assumed that the density at the edges of the plate is wholly due to general sky-illumination not originating in the corona. The intensity represented by this density was then subtracted from all other measured intensities. It was then assumed that the effects of halation did not extend beyond 6 mm from the image of the limb of the moon. The remaining intensities across the moon were taken to represent light scattered from the corona.

The problem which then presented itself is analogous to that arising in the study of the law of radiation along a diameter of the sun. From observations made with the 150-ft. tower telescope it was found that the light scattered from the sun upon any point outside the limb where this law can be tested is represented by assuming that the amount contributed by any small area of the disk to any other small area may be expressed by the empirical formula:

$$\Delta C = \frac{kI\Delta A}{r^2+Z}. \qquad (7)$$

As applied to the corona, ΔC is the amount of light scattered from a small area ΔA, at a distance r. The constants k and Z were varied until the amount of scattered light calculated by the integration of equation (7) agreed as well as possible with that observed over the region of the moon not affected by halation. With the intensity of the light producing the densest square as unity, the corrections for

[1] *Études sur la Distribution de la Lumière dans la Couronne Solaire* (Stockholm, 1919), p. 28.

points situated in the middle of each zone arising from scattered light from the whole corona are as given in Table III. The correction H for halation, found by subtracting the intensities of the scattered light across the moon from the total intensities, is also given in Table III.

Table IV shows the resulting mean intensities in the various zones for each plate, corrected for scattered light and halation by Table III, and also for general sky-illumination as in Table II.

TABLE IV

MEAN INTENSITY FOR DIFFERENT ZONES OF THE CORONA CORRECTED FOR GENERAL SKY-ILLUMINATION, HALATION, AND SCATTERED CORONAL LIGHT

ZONE NUMBER	MEAN RADIUS	I, SEED 30 PLATES, $\lambda=4500$ A				I, ILFORD, $\lambda=6500$ A	
		2-Sec.	15-Sec.	Mean Obs.	Comp.	Obs.	Comp.
1	1.11	0.563	0.514	0.538	0.502	0.815	0.781
2	1.27	.201	.242	.221	.223	.277	.304
3	1.43	.094	.120	.107	.109	.126	.131
4	1.59	.051	.056	.054	.058	.065	.063
5	1.75	.030	.032	.031	.033	.031	.032
6	1.91	.021	.021	.021	.019	.016	.017
7	2.07	.015	.013	.014	.012	.008	.010
8	2.23	.011	.008	.010	.007	.006	.006
9	2.39	.006	.005	.006	.005	.....	.004
10	2.55	0.002	.003	.003	.003	.....	.002
11	2.71	.....	.001	.001	.002	.....	.001
12	2.87	.....	.001	.001	.002	.....	.001
13	3.03	.....	0.000	0.000	0.001	.....	0.001

As before, the mean radius of each zone is expressed in terms of the sun's radius. The fifth column gives the mean intensity as determined from the two Seed 30 plates, and the sixth column the corresponding intensities calculated from

$$I=\frac{I_0}{R^6}, \tag{8}$$

where I is the mean intensity at any point in the corona situated a distance of R solar radii from the center of the sun, and where $I_0=0.920$ is the intensity at the limb of the sun. The seventh column gives the mean intensities derived from the Ilford plate with red filter, and the eighth column, values computed from

$$I=\frac{I_0}{R^7}, \tag{9}$$

where $I_0 = 1.581$. The data from Table IV are plotted in Figure 2, the abscissae being distances from the center of the sun in solar radii, and the ordinates, the energy in units of the light which produced the densest square. The circles represent the observed intensities from the Seed 30 plates, and the full-line curve those cal-

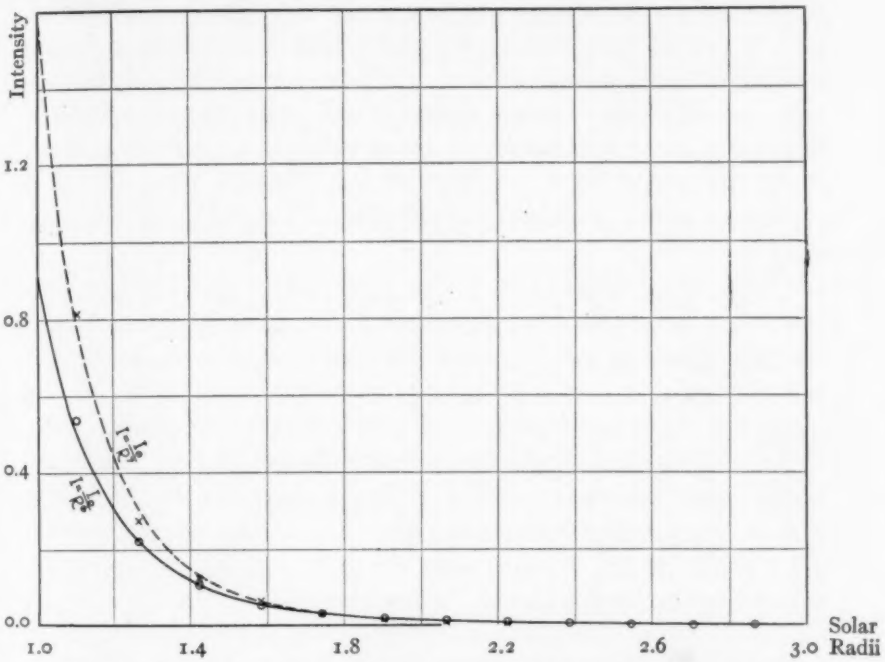


FIG. 2.—Variation of mean intensity of corona with distance from the sun's center. Circles represent measures on Seed 30 plates; crosses, measures on the Ilford panchromatic plate exposed with red filter.

culated from the inverse sixth-power formula (8). The crosses indicate the observed intensities from the Ilford plate with red filter, while the dotted curve represents the inverse seventh-power formula (9).

If we correct the value of I_c used in equation (4) for scattered light (0.024) by Table III and use the value of the solar constant reduced to mean distance, the energy emitted from a square minute of arc of the corona at mean distance may be obtained from equation (8) by using the constant $I_0 = 0.050 \times 10^{-7}$ cal. cm^{-2} min.$^{-1}$ For equation (9) $I_0 = 0.073 \times 10^{-7}$ cal. cm^{-2} min.$^{-1}$

Since the intensity of the blue light (λ 4500) varies inversely with the sixth power of the distance from the sun's center, and of the red light (λ 6500) inversely with the seventh power, it follows that the ratio of blue light to red light varies directly with the distance from the sun's center. In other words, the corona becomes bluer as we go outward from the sun, or redder as the sun's limb is approached. This is not what we should expect from an atmosphere of incandescent particles around the sun, since the temperature of the particles should increase toward the sun, thus causing the proportion of blue radiation to increase in the opposite manner to that observed. Molecular scattering of sunlight or luminescence from electrical discharges would probably produce effects in accord with what we find.

Both Turner[1] and Schwarzchild[2] have deduced the inverse sixth-power law from photographic observations, although others[3] have obtained formulae ranging from the inverse square to the inverse eighth power, with modifications of the origin of co-ordinates. In discussion of observations with the photo-electric cell, probably the inverse sixth-power should be used; but for visual light, a slightly higher power should be applied, although the effect on the results will be small, quite beyond the accuracy of the determinations. Since the maximum of solar energy lies in the region of wave-lengths covered by the Seed 30 plates, the inverse sixth-power law is adopted for the following discussion, which relates to the measures of total radiation with the thermocouple.

We may express the energy emitted by that portion of the corona projecting beyond a disk of radius r concentric with the sun by the integral

$$E=I_0\int_0^{2\pi}\int_r^{\infty}\frac{r\,dr\,d\theta}{r^6}. \tag{10}$$

The value of this integral is

$$E=\frac{\pi I_0}{2r^4}. \tag{11}$$

At the time of eclipse, a square solar radius equaled 830 square

[1] *Popular Astronomy*, **14**, 548, 1906.

[2] *Astronomische Mitteilungen der Königlichen Sternwarte zu Göttingen*, **13**, 1906.

[3] Mitchell, *Eclipses of the Sun*, p. 342.

minutes of arc. Using $I_0 = 0.050 \times 10^{-7}$ cal. cm^{-2} min.$^{-1}$ per square minute of arc and $r = 1$, we find

$$E = 20.9 \times 10^{-7} \text{ cal. cm}^{-2} \text{ min.}^{-1} \tag{12}$$

This is the radiation outside the earth's atmosphere for the whole corona at mean distance. We must correct the value of E obtained in equation (5) for the overlapping of the moon before comparing it with equation (12).

From equation (11) it follows that the factor c, which reduces the observed radiation from the corona to its total value, is given by

$$c = \left(\frac{R}{r}\right)^4, \tag{13}$$

where r is the apparent radius of the sun, and R the apparent radius of the overlapping moon as seen from the eclipse station. For Middletown, this factor was 1.107. When this factor is applied, the value of E from equation (5) becomes

$$E = 21.4 \times 10^{-7} \text{ cal. cm}^{-2} \text{ min.}^{-1}, \tag{14}$$

which agrees well with equation (12).

Applying the factor 1.107 to the ratio of coronal light to full-moon light given in equation (6) we find

$$\frac{\text{Whole corona}}{\text{Full moon}} = 0.52. \tag{15}$$

It is interesting to note in this connection that the maximum correction for overlapping moon is 1.38, or 0.35 magnitude, that the surface brightness of the corona at the sun's limb on the equator is about 1.4 times as great as the visual brightness of the full moon, and that one-half the light of the corona comes from a zone extending only 3′ from the limb of the sun.

The factors which correct the observations of Kunz and Stebbins on June 8, 1918, and of Briggs on September 20, 1922, for overlapping moon are 1.100 and 1.245, respectively. Applying these factors, we obtain the results in Table V, which shows the ratios of the whole corona to full moon and the radiation emitted in cal. cm^{-2} min.$^{-1}$ The last column gives the corresponding solar constant.

Probably the material is insufficient to warrant generalizations, but Table V suggests that the total light of the corona has not varied much during the last seven years at least, and that such variation as is shown is in harmony with the variation in the solar constant, although of greater amplitude.

DETECTION OF THE CORONA WITHOUT AN ECLIPSE

The principal difficulty presented by the problem of detecting the corona without an eclipse is not that the amount of energy to be measured is itself small, but rather that it has superposed upon it the enormously greater illumination near the sun produced by scattering in our atmosphere and in the telescope. No measurements of this scattered light have been made with the apparatus used at

TABLE V

RADIATION FROM THE WHOLE CORONA

Eclipse	Observers	Whole Corona / Full Moon	Radiation Cal. Cm^{-2} $Min.^{-1}$	Solar Constant Cal. Cm^{-2} $Min.^{-1}$
June 8, 1918.....	Kunz and Stebbins	0.55	22.8×10^{-7}	1.94
Sept. 20, 1922.....	Briggs	.41	16.5×10^{-7}	1.89
Jan. 24, 1925.....	Pettit and Nicholson	0.52	21.4×10^{-7}	1.93

the eclipse, but observations with the 150-ft. tower telescope under the best conditions on Mount Wilson showed that its value at the limb of the sun is about 2.5 per cent of the mean over the disk. Probably the elimination of the fixed mirror and lens might reduce this value to 1.5 per cent.

Since the scattered light varies less rapidly than the coronal light with the distance from the center of the sun, it follows that the most advantageous place for measurement is near the limb of the sun. Here, the intensity of the coronal light is 1.5×10^{-6} of the mean over the disk. In other words, the scattered light is approximately ten thousand times the intensity of the coronal light.

Suppose, now, that we explore the region about the sun by revolving one junction of a thermocouple at a fixed distance from the limb, while the other remains at a fixed point in the orbit of the first junction. The variations in the corona are 50 per cent of its intensity in the equatorial regions, as may be seen from the intensity curves

in Figure 1. Hence, if we assume that the scattered light is constant, the total variation in the observed radiation, scattered light plus corona, will be one-twenty thousandth (5×10^{-5}) of its value. It is probable that the changing transmission of the atmosphere, changing distance of the thermocouple junction from the limb of the sun due to mechanical difficulties, bad seeing, and other sources of error would produce, from second to second, variations in the observed radiation greater than this value.

As no measurements of the sky-radiation at the limb of the sun free from instrumental scattering are available, it is not possible to estimate how small the intensity of the scattered light near the sun can be made; hence definite judgment in the matter must be deferred until such measurements are at hand. Unless the amount of scattering can be reduced to at least 1 per cent of the value assumed here, there is little hope of detecting the corona without an eclipse by any radiometric method, for the distribution of the coronal light is, apparently, nearly like that of the sun, so that screens or dispersion apparatus will be of no avail.

CONCLUSIONS

Our observations show that:

1. At the eclipse of January 24, 1925, the intensity of the coronal radiation at points 4′.6 from the east and west points of the moon's limb was 5.40×10^{-7} of the integrated solar radiation.

2. The energy to the violet of $1.3\,\mu$ is somewhat greater in coronal radiation than in sunlight, although the difference is small.

3. The long-wave radiation in the corona beyond $5.5\,\mu$ is inappreciable, so that glass or quartz windows may be used on the radiation apparatus.

4. The light from the visible corona was one-millionth (10.1×10^{-7}) as great as sunlight, and 0.47 that of the full moon at mean distance. When corrected for overlapping moon, these values become 11.2×10^{-7} and 0.52, respectively, or 21.4×10^{-7} cal. cm^{-2} $min.^{-1}$

5. There is some evidence that the amount of coronal light varies with the solar constant, but with greater amplitude. Should this prove to be true, the light from the corona cannot be reflection or radiation from solid or liquid particles, for in that case its variations

would have the same amplitude as variations in the solar radiation.

6. The intensity of the radiation emitted by a point in the corona as determined from the Seed 30 plates varies inversely as the sixth power of the distance from the center of the sun.

7. The ratio of the amount of blue light to that of red light varies directly with the distance from the center of the sun, that is, the inner corona is redder than the outer corona. This is what may be expected if the coronal light arises from luminescence, or from molecular scattering in a gaseous atmosphere, but is opposed to the theory involving solid or liquid particles.

8. The difference between the radiation of the whole corona and that observed outside the moon's limb may be as much as 0.38 magnitude.

9. The surface brightness of the corona at the limb of the sun is about 1.4 times that of the full moon, and half the light of the corona comes from a zone extending only 3′ from the limb of the sun.

10. It is not likely that the corona can be detected without an eclipse by radiometric methods unless the scattered light near the sun can be reduced to about one-hundredth that observed on Mount Wilson.

MOUNT WILSON OBSERVATORY
June 1925

NOTE ADDED OCTOBER 7, 1925

Measurements of the coronal radiation transmitted by one centimeter of glycerine made by Stetson and Coblentz at the eclipse of January 24, 1925, this *Journal*, September, 1925, p. 128, differ radically from our measurements of the radiation transmitted by one centimeter of salt water. Since the transmissions of salt water and glycerine are approximately the same, it seems advisable to

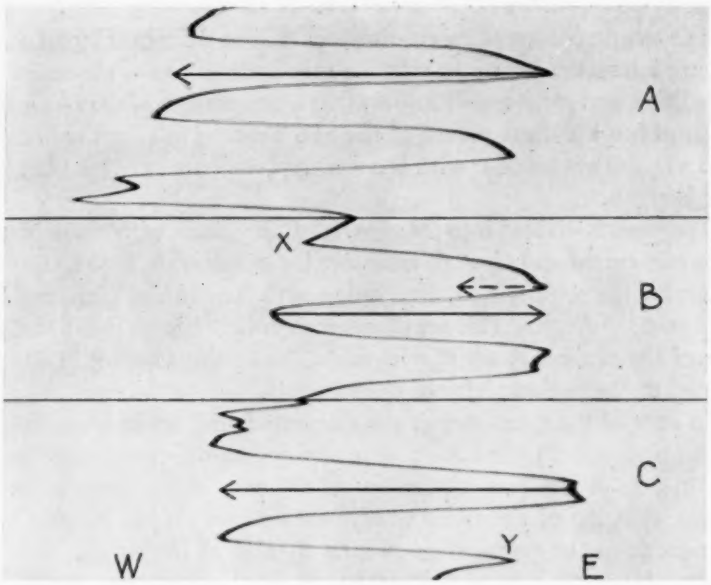


FIG. 3.—Galvanometer deflections measuring coronal radiation: *A*, total energy; *B*, water-cell transmission; *C*, cover-glass transmission. Deflections marked *X* and *Y* have been rejected as obviously defective. The letters *E* and *W* indicate that, at the time the corresponding deflections were made, the hot junction of the compensated thermocouple was on the image of the corona east and west of the moon, respectively, 4'.6 from the limb.

show the original photographic record of the galvanometer deflections. Figure 3 is a reproduction of the negative taken with the photographic registering device, three-fourths the original scale. The full-line arrows indicate the deflections as measured, while the dotted arrow in *B* indicates, on the same scale, the deflection corresponding to the transmission observed by Stetson and Coblentz on the west side of the sun. Their value of the ratio of transmitted to total energy is approximately one-third that found by us.

REVIEWS

The Rare Earths: Their Occurrence, Chemistry and Technology. By S. I. LEVY, Cambridge. Second edition. New York: Longmans, Green & Co.; London: Edward Arnold & Co., 1924. 8 vo. Pp. xiii+362. Figs. 11. $6.00 net.

The second edition of this useful book will be welcomed by all persons who are interested in any way in the rare-earth group of elements. The first edition was so favorably known that a comparison of the two editions will furnish a sufficient review of the new volume, but for the benefit of those who are not familiar with the work, a brief outline of the plan of the book is given.

The book is divided into three parts. Part I deals with the occurrence of the rare earths and gives an extensive list of minerals, with a statement concerning the composition, description of the crystalline form, and habitat of each. Following this are chapters devoted to more detailed discussions of the various types of minerals. The closing chapter in Part I is devoted to the radioactivity of the minerals.

In Part II the chemistry of the elements is treated in seven chapters which are devoted to various phases of work on the rare earths, such as breaking up of the ores, separation of the rare earths from other substances, splitting of the group of rare earths into subgroups, and finally the separation and purification of each member of the group.

Part III is devoted to the technology of the elements. In this part are given in detail the points of interest connected with the incandescent-mantle industry, including the treatment of monazite sand, the manufacture of mantles from cotton, ramie, and artificial silk; the final chapter is devoted to the various other applications which have been tried for the utilization of the elements included in this work.

The second edition resembles the first not only in form and appearance, but also in style, arrangement, and scope. Many of the original chapters have been preserved almost intact, with a few added sentences or paragraphs which contain the new material. The most noticeable change in plan is the entire omission of titanium from the second edition. The author considers this change desirable because information concerning titanium is much more easily available now than it was when the first edition was prepared. Since titanium is not a rare earth and its chemistry and technology are not intimately associated with the rare-earth group,

the omission brings the context more nearly in line with the title of the book. The author includes zirconium and thorium in the new edition in the same manner as in the first. A brief summary of the chemistry of these elements "is necessary in any complete account of the Rare Earths." The material concerning these two elements is well selected and skilfully presented, but one cannot help wondering if the space devoted to their technology is not greater than their relationship to the rare earths justifies in a book devoted to this group of elements. Information concerning both zirconium and thorium is also now quite readily available from other sources.

The omission of titanium has made it possible to leave out three entire chapters and a few paragraphs in certain other places. The total amount of material omitted in this manner covered about fifty pages in the first edition. In the second edition the author has added more than enough new material to fill these pages, so the book is slightly larger than its predecessor.

One observation which shows the author's carefulness in his editorial work is the fact that in only a few places has he been compelled to change a statement that was made in the first edition. In perhaps fifteen cases a paragraph or part paragraph has been entirely changed in the new edition. The chapter on radioactivity has been entirely rewritten and somewhat extended, owing to the material advances made in this field. An Author Index has been added, which will greatly increase the usefulness of the volume. Most of the new material has been added by inserting a sentence or paragraph here and there in order to bring the discussion up to date. More than seventy-five such additions can easily be counted throughout the volume. The insertions are not fragmentary, but they have been added skilfully so that the new edition reads smoothly in all places. Apparently the author has scanned the literature with unvarying faithfulness, for one looks in vain for important omissions of newly published information. The author has been successful in his announced intention of taking "account of all work appearing in the literature up to the end of June, 1924." The temptation to devote too much space to new material has been successfully resisted.

The mechanical features of the book are entirely satisfactory, except in the case of the binding, which seems to be somewhat flimsy.

In the second edition Dr. Levy has fully lived up to the reputation established by his earlier publication. The book is worthy of a place in the working library of every person who is interested in inorganic chemistry, and is indispensable to investigators in the rare-earth group.

B. S. HOPKINS

The Vault of Heaven. By SIR RICHARD GREGORY. New York: E. P. Dutton & Co., 1923. 8vo. Pp. vii+202. 25 diagrams and 36 half-tones. $2.50.

The author's explanatory heading, "An Introduction to Modern Astronomy," exactly characterizes the nature of this book. It is a new edition of a book published in 1893, but revision has been done with sufficient completeness to quite remove the atmosphere of second editions. It is essentially a new volume. Intended for popular reading, the book differs from the ordinary volume of this type in conveying an impression of sincere scientific simplicity. To cite but one instance, there is a marked absence of the usual fantastic drawings of lunar and planetary landscapes, so familiar in popular works. Here the illustrations are well-chosen photographs of the heavens. The work will not serve as a text-book. The author has touched but lightly upon the elementary facts, pointing always to the modern trend of investigation. Solar spectroscopy perhaps receives his fullest consideration. He places much emphasis on historical development.

JAMES F. KOEHLER